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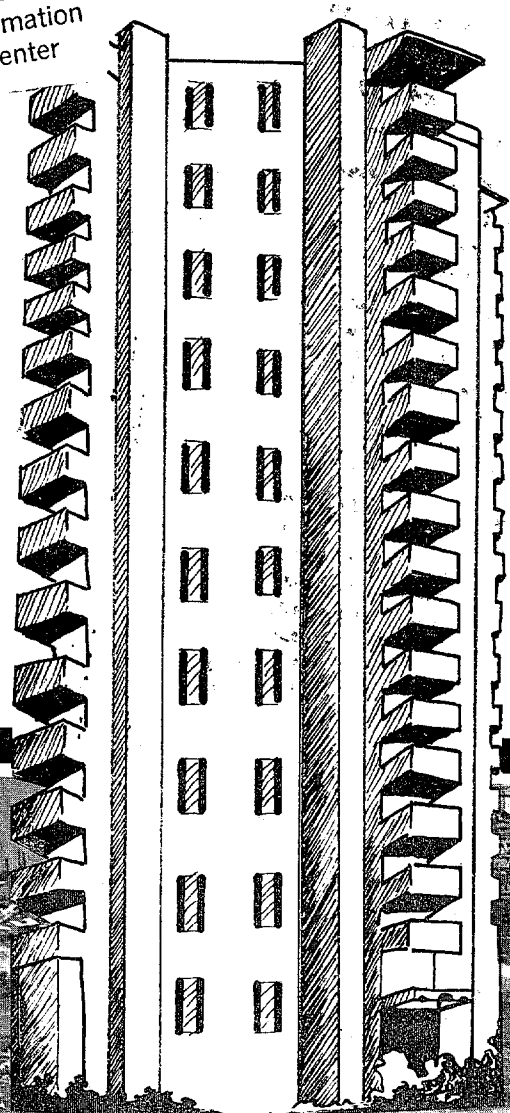
Model Minimum Hurricane Resistant Building Standards for the Texas Gulf Coast



...al + Marine Council

MODEL MINIMUM HURRICANE-RESISTANT BUILDING STANDARDS FOR THE TEXAS GULF COAST

CONDUCTED BY
THE TEXAS COASTAL AND MARINE COUNCIL

SENATOR A. R. "BABE" SCHWARTZ, CHAIRMAN
JOE C. MOSELEY II, EXECUTIVE DIRECTOR

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General Land Office of Texas
Bob Armstrong, Commissioner

U.S. DEPARTMENT OF COMMERCE NOAA
COASTAL SERVICES CENTER
2234 SOUTH HOBSON AVENUE
CHARLESTON, SC 29405-2413

SEPTEMBER, 1976

This study was funded in part through financial assistance provided by the Coastal Zone Management Act of 1972, administered by the Office of Coastal Zone Management, National Oceanic and Atmospheric Administration.

TEXAS COASTAL AND MARINE COUNCIL

July 21, 1976

The Honorable Bob Armstrong
Commissioner
General Land Office
Stephen F. Austin Building
Austin, Texas

Dear Commissioner Armstrong:

Enclosed is a copy of the report entitled, "Model Minimum Hurricane-Resistant Building Standards for the Texas Gulf Coast," that the Texas Coastal and Marine Council contracted to produce for the General Land Office under the terms of IAC(76-77)717.

This report contains three principal efforts:

- An analytical procedure for determining the degree of exposure to reasonably "probable" hurricane conditions along the Texas coast.

- A model minimum building standard, in a building code format, that, if implemented as an adjunct to common codes--such as the Southern Standard Building Code--should reduce damages due to hurricane forces. Application of these standards would raise the building cost only 3-8%.

- A thorough discussion of the natural hazards of the Texas Gulf coast.

The Council is also working on a similar effort under a mandate of the Texas Legislature (S.R. 268) to develop model minimum standards and to examine other related issues. This report is due in about six months. We would appreciate receiving copies of any comments that you may receive on this report for incorporation into our report to the 65th Texas Legislature. We are currently reviewing this document in detail with the affected professional groups (engineers, contractors, architects, insurance and local government) and anticipate some revision.

If we can be of any further assistance on this matter, please let me know.

Sincerely,

Joe C Moseley II

Joe C. Moseley II, P.E.

POST OFFICE BOX 13407/AUSTIN, TEXAS 78711/ PHONE (512) 475-5849

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PREFACE

Hurricanes have been a major threat to life and property along the Atlantic and Gulf coasts. Although catastrophic loss of life has been avoided since the 1900 Hurricane killed 6,000 persons in Galveston, Texas, conditions are now developing which lead officials to fear another major killer. The contributing factors include the following:

- Rapidly increasing development in low-lying coastal areas, many of which are reachable only over long stretches of exposed low highways.

- Massive influx of persons from non-coastal areas who fail to appreciate how devastating a major hurricane can be. This problem is compounded by the fact that many persons have experienced a near miss or only a minor storm and thus have a casual attitude toward these storms.

- Warning systems have improved much in recent years, contributing to complacency among both officials and the public. However, a plateau has been reached, and additional significant improvements are not anticipated.

The best way--from a technical, political, and economic standpoint--to significantly reduce hurricane damage on a wide scale is through the use of hurricane-resistant building practices.

If proper standards are developed and thoughtfully applied in a manner consistent with the exposure to hurricane dangers, damage can be greatly reduced at a modest cost. Since a substantial portion of the population inevitably refuses to evacuate during a warning, the use of stronger structures will obviously result in lower loss of life during the storms.

This report was prepared to serve two purposes:

1. Develop for the Texas Coastal Management Program of the General Land Office hurricane-resistant building standards as part of their overall coastal management program effort.

2. Partially satisfy the requirements of S.R. 268, which calls for examination of hurricane hazards, development of hurricane-resistant performance criteria, drafting of a model minimum building standard, and

preparation of institutional alternatives for implementation.*

While this procedure and these standards were developed with the Texas coast in mind, almost all elements are generally applicable for all coastal states from Texas to Maine.

To accomplish the tasks set out in S.R. 268, a group of experts was assembled. Those persons, along with their principal responsibilities, are as follows:

1. Determination of Hazard Areas and Types of Destructive Forces Associated Therewith:

   Dr. Robert Simpson, consulting meteorologist, former director of the National Hurricane Center of the National Weather Service and world-renowned hurricane expert. Dr. Simpson was responsible for devising the overall methodology for delineating hazard areas. Dr. Robert Morton, Bureau of Economic Geology, University of Texas at Austin. Dr. Morton shared the responsibility for delineating hazard areas and provided guidance on geological conditions and development. Dr. John Freeman, director of the Institute for Storm Research, University of St. Thomas in Houston. Dr. Freeman, in cooperation with Dr. Simpson, developed the technique for determining the inland boundaries of surge distribution.

2. Drafting of Model Minimum Building Standards:

   Mr. Herbert Saffir, P.E., consulting engineer, Coral Gables, Florida, a well-known expert on hurricane resistant codes. Helped to set minimum standards and assisted with standards development. Dr. Charles Hix, P.E., consulting engineer and staff member of the Engineering Extension Service, Texas A&M University. Dr. Hix drafted the model standards. Mr. James A. Goldston, P.E., President of the Goldston Construction Company, Corpus Christi. Served in a consultative capacity to insure that decisions/actions were reasonable in view of construction practices and conditions along the Texas coast.

3. State government officials involved in the preparation of this report were: Mr. Art Eatman, P.E., of RPC, Inc., who served as project

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* *Follow-up work is continuing in a report of the other aspects that will be ready to submit to the Texas Legislature in January of 1977.*

officer for the General Land Office. Mr. Frank Cox and Mr. Ashley Eledge, Governor's Office, Division of Disaster Emergency Services, served as liaison with that office. The Division of Disaster Emergency Services is responsible for disaster planning. Dr. Joe Moseley, P.E., Executive Director of the Texas Coastal and Marine Council, was responsible for overall conceptualization and management of the project.

SECTION I

INTRODUCTION

Hurricanes pose a very significant threat to lives and property in coastal areas. Texas is hit by a hurricane on the average of once every other year. Only recently has attention in coastal management deliberations been focused on hurricane hazards.

Development in Texas' coastal areas is increasing, and this trend will continue. This is to be expected, as the coast offers many economic and aesthetic amenities. Since hurricanes are inevitable, it is desirable to develop hazard-prone areas in a fashion that will (a) avoid as many hazards as practical; (b) withstand those forces that cannot be avoided when economically feasible; (c) absorb the inevitable losses; and (d) <u>most important</u>, reduce the loss of life as much as possible.

One viable way to accommodate growth in high-risk areas is to develop and implement minimum building standards that will reduce the hurricane risk to life and will reduce the risk to property to an acceptable level and in an equitable manner. Such action sounds deceptively simple but requires a complex and controversial mix of scientific, engineering, legal and political actions. This report presents such an approach. Principal elements include:

- A discussion of the hurricane-related processes impacting the Texas coast;

- A description of the nature and magnitude of the destructive forces associated with the hurricane process, and the synthesis of parameters for a "Texas Design Hurricane;"

- An analytical procedure, based upon accepted scientific methods, for spatially delineating the varying degrees of exposure to the design hurricane's destructive forces in coastal areas--i.e., establishing "hazard zones;"

- A set of minimum performance criteria for structures in each of the hazard zones, and

- A draft minimum model building standard which complements the Southern Standard Building Code and which contains hurricane-resistant wind and flood requirements which are compatible with accepted design and construction practices and economic realities. This model can be used to implement the performance criteria in each hazard zone.

MODEL STANDARDS

Actions by other entities, standard engineering practices, and experience were all heavily relied upon in an attempt to make the product--i.e., the MODEL HURRICANE BUILDING STANDARDS--as practical as possible. The result is a model code that is:

- Based on common design and construction practices with minimal modifications for wind-resistant and flood-resistant requirements (where applicable);

- Readily usable by practicing architects and engineers with a minimum of special efforts;

- Very economical to the builder/consumer. (Without any cosmetic frills,* it is estimated that the use of this standard, with its hurricane-resistant provisions, will add a maximum of 3-8% over the basic structural cost of the same building constructed to the Southern Standard Building Code now commonly used.**)

- In its present form, the Model Standard could be easily adopted by local governments, and, if they already use the Southern Standard Building Code, incorporation of these special provisions would be very simple.

LEGAL AND INSTITUTIONAL CONSIDERATIONS

Under Texas law, municipalities have the power to adopt ordinances, including building codes. With few exceptions, counties do not have this power. Thus, under existing law, implementation of building standards will

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* *Opponents of any special hurricane-resistant codes often point to codes like that used in Coral Gables, Florida, and note that use of such a code may greatly increase the cost of a structure. However, such codes frequently contain many additional provisions for architectural appearance, etc., that have nothing to do with hurricane resistance. A special analysis is underway which develops detailed cost estimates for common coastal structures, both using and not using these special hurricane-resistant standards. It will be ready by December, 1976.*

** *Appendix C to Section IV contains a listing of Texas coastal municipalities using the Southern Standard Code, and other common Texas practices.*

generally fall to coastal municipalities. Legislative action could extend this power to coastal counties, if it were politically palatable. The state, although it has no general authority to set or enforce building codes, can do so in special hazard situations, such as under the disaster planning and special, high-risk insurance statutes.

Hurricanes Carla and Celia caused many coastal residents to lose their insurance. As a result, the Legislature established the Texas Catastrophe Property Insurance Pool Act (passed in 1971) which requires all property insurers in the state to pool their resources and provide insurance in high-risk areas. Special rates may be charged in the high-risk areas, and upon approval of the Insurance Board, special building requirements may be imposed in such areas as a condition of insurability.*

The 1973 Texas Disaster Act, which was updated in 1975, was the first of its kind in the nation, and brings a major new dimension to the state involvement with disasters. Previously, virtually all state disaster and civil defense activities had been oriented to rescue, relief and recovery. The new law stresses preventive measures by establishing a new policy and setting up new administrative and legal mechanisms. One provision specifically authorizes the governor to suspend any local building code or land use ordinance and place one of his own choosing in effect if he finds a disaster or a threat of disaster. This would include imposition of such requirements in areas where none now exist. Implementation is still in its infancy, and, since some of the preventive steps will be unpopular in many quarters, it is impossible to preduct the ultimate effectiveness of this law.

In 1975 the Legislature passed a resolution (S.R. 268) which mandated the development of model minimum building standards for high-risk coastal areas. This report is part of the response to that mandate.

The federal government has many programs and policies that relate to disaster exposure, risk and recovery. The Corps of Engineers has countless projects aimed at the construction of protective facilities to minimize damage from flooding and erosion. The nationally subsidized federal flood insurance program, which requires participation of any new construction utilizing federal guaranteed loans, requires local governments to adopt flood management programs. This has been unpopular in many quarters, and the ultimate effect is uncertain.

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* *This provision has never been utilized, although there is currently (Summer '76) an effort to apply it to mobile homes. Some believe this needs clarification.*

The Disaster Relief Act of 1974 constitutes a major change in the federal approach, shifting much emphasis from recovery to prevention. Relatively little has been done by the responsible agency, HUD, to implement this law. When such an attempt is made, there may be more protest than there was over the flood insurance program. Another well-known federal effort is the hurricane warning system headed by the National Weather Service.

While strong governmental actions are theoretically possible--such as a construction moratorium in high-hazard areas or the direct establishment and enforcement of state building codes--they are unlikely. Such actions would raise Constitutional questions about the use of private property, and could severely restrict the opportunity of citizens to use and enjoy coastal resources. Considering the size and diversity of the Texas coastal area, such actions would be impractical to administer. More realistic avenues are available.

- Increased public awareness of the potential hazards and actions that individuals can take to counter them is a first step. Two specific actions should be explored: (a) the current Hurricane Awareness Program should be continued for current coastal residents, and (b) a disclosure of potential hazards should be provided to all new residents. The purpose of the latter is not to "scare" potential buyers away, but to inform them of hazards and appropriate countermeasures.

- Insurance availability and cost should be tied to the strength of a given structure, and its exposure to a hurricane hazard. Currently, the Texas Catastrophe Property Insurance Pool Act has very nebulous provisions for basing rates on the strength of a structure and none on its degree of exposure except in the Pool area. The possibility of such an amendment should be examined.

- The current mix of federal and state disaster related programs is very complex. In some cases, the laws and regulations seem to work against each other, or even to promote the creation of "disaster-prone" situations.* The state should make a careful assessment of the impact of these programs.

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* *Assessment of Research on Natural Hazards*, *G.F. White and J.E. Haas, MIT Press: 1975.*

These and other matters are still being considered by the Texas Coastal and Marine Council as part of its legislative mandate under S.R. 268. The report on this is due in December, 1976.

DELINEATION OF HAZARD ZONES

A first step in developing a hurricane-resistant building standard is to spatially describe the physical forces of the hurricane in a quantitative manner. Much work has been done on the subject. A relatively simple procedure was developed to be used in conjunction with developing and applying minimum hurricane-resistant standards. This procedure utilizes a combination of analytical procedures and prima facie conditions* and draws heavily on existing practices.

The result is four "zones," reflecting four different levels of exposure. They are:

Zone A - Scour
- Battering with Debris
- Flooding
- Wind (140 mph)

Zone B - Battering with Debris
- Flooding
- Wind (140 mph)

Zone C - Flooding
- Wind (140 mph)

Zone D - Wind (140 mph)

Figures I-1 and I-2 illustrate the four zones and the type of destructive forces present in each. Section III is devoted entirely to how to determine the degree of exposure and Section II contains an extensive discussion of the processes involved. A brief discussion of a typical situation in each exposure zone is useful.

- Zone A: An example of Zone A may occur on a barrier island and near the beach. The full fury of the storm's wind obviously strikes here. Much of the area is likely to be below 15 feet above sea level, and flooding is very possible. The waters could be moving at a velocity of several knots and be topped with violent waves of 5-10 feet. The water mass itself can exert a significant force, but this is compounded greatly with floating objects

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* *As used herein "prima facie conditions" refer to physical evidence, meteorological, geological, topographical, or hydrological, which may be in disagreement with the analytical results. In such cases, the specified prima facie evidence will govern.*

such as boats, vehicles, parts of other structures, etc. Few, if any, residential structures could be expected to survive the impact of a one-ton object moving at 10 feet per second (7 miles per hour). This violent water action can also be a very effective "ditch digger" and cause scour around foundations, walls, etc., and undermine structures that would otherwise survive. Figure I-3 shows what kind of damage scour can do. While this condition will usually occur on a barrier island or on a Gulf-front area of the mainland where there is no barrier island, it could also occur on the shores of the major bays.

- Zone B: The middle part of a barrier island, not at an exceptionally high elevation, and away from a washover channel would likely fall into Zone B. Such a place would be subject to the same destructive forces as Zone A, except scour, and could be located on the mainland near a bayshore.

- Zone C: This zone could occur on the mainland at a considerable distance inland. Hurricane Carla (1961) caused saltwater flooding 10-15 miles inland across the low-lying coastal plain. Flooding is apt to occur even further inland along the many bayous, streams and other watercourses.

- Zone D: Hurricane force winds (74 mph) may extend hundreds of miles inland. However, the extreme winds, i.e., 140 mph, begin to reduce rapidly as the storm loses energy as it moves over land. A procedure is given in Section III for estimating this wind reduction away from the water.

These hazard zones are defined for a fairly narrow purpose: to enable a competent engineer to estimate the physical forces that are likely to be encountered at a specific building site. This information is then used to select the proper specifications from the model standard. When the specific parameters from the "Design Hurricane" are used in the analytical procedure, the result will be a location in one of these zones.

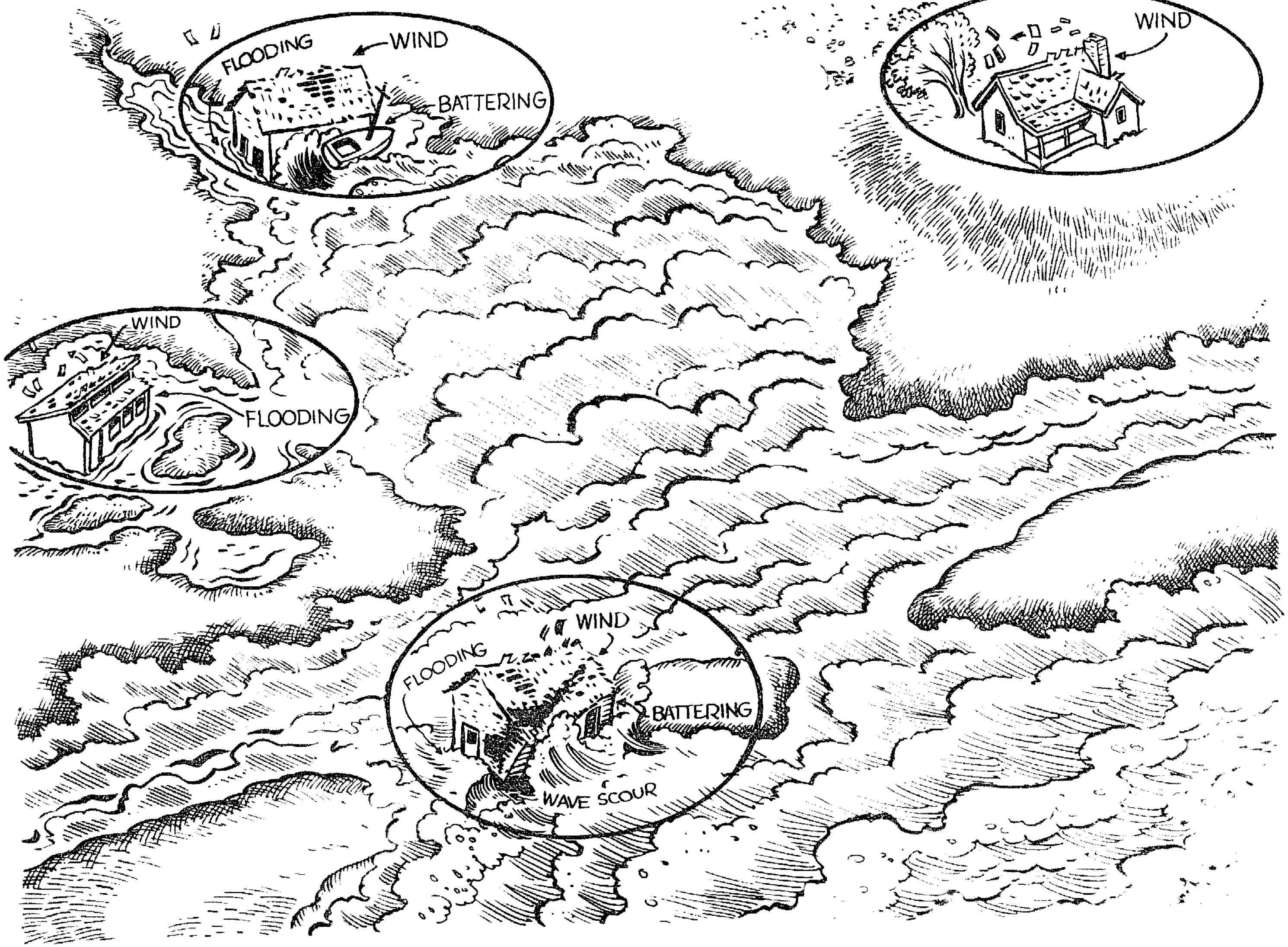


FIGURE I-1

TYPES OF HURRICANE DAMAGE FOR DIFFERENT DEGREES OF EXPOSURE

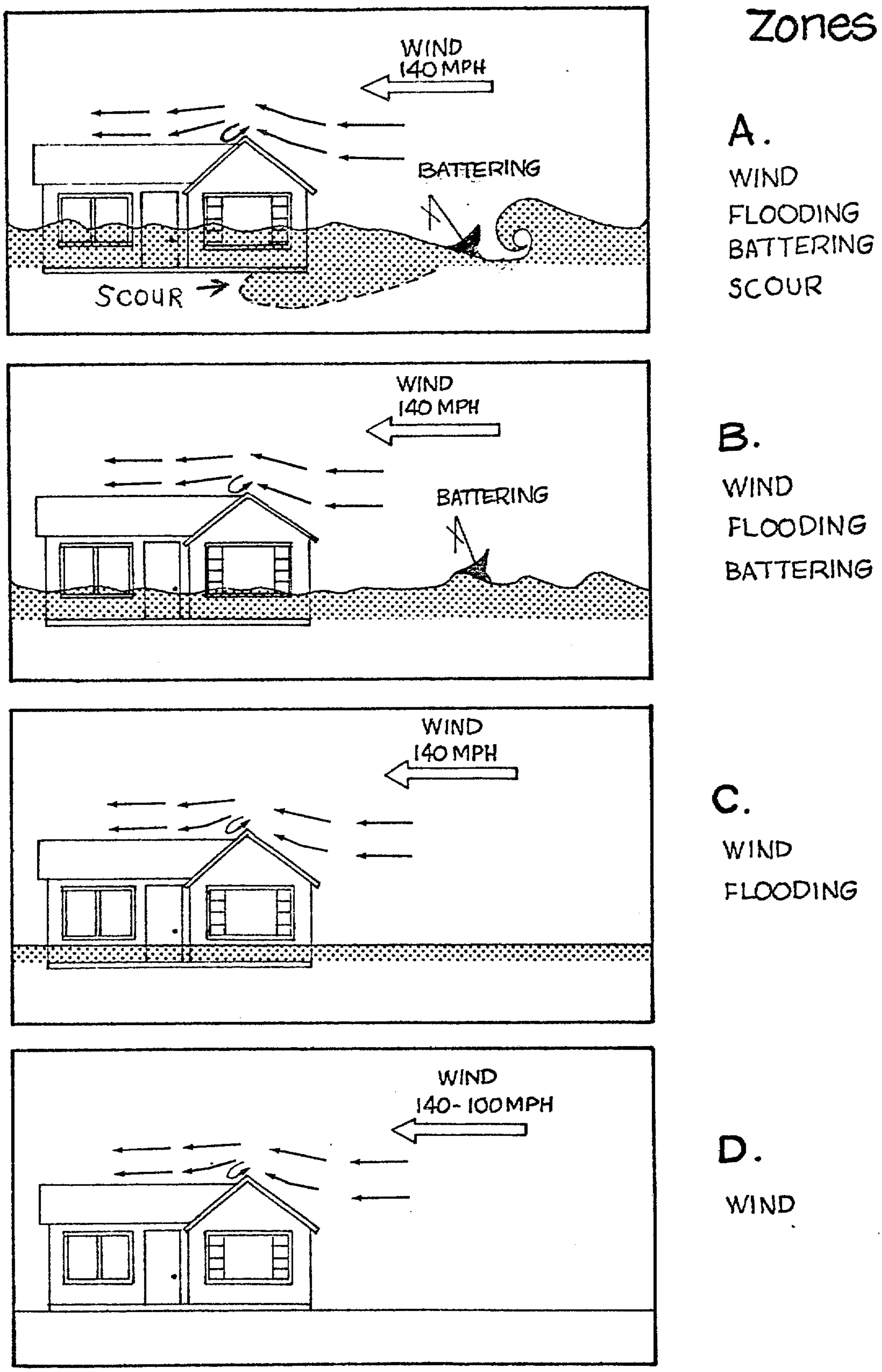


FIGURE I-2

(SAME AS FIGURE II-1)

SCHEMATIC REPRESENTATION OF HAZARD ZONES A TO D IN TEXAS COASTAL AREAS.

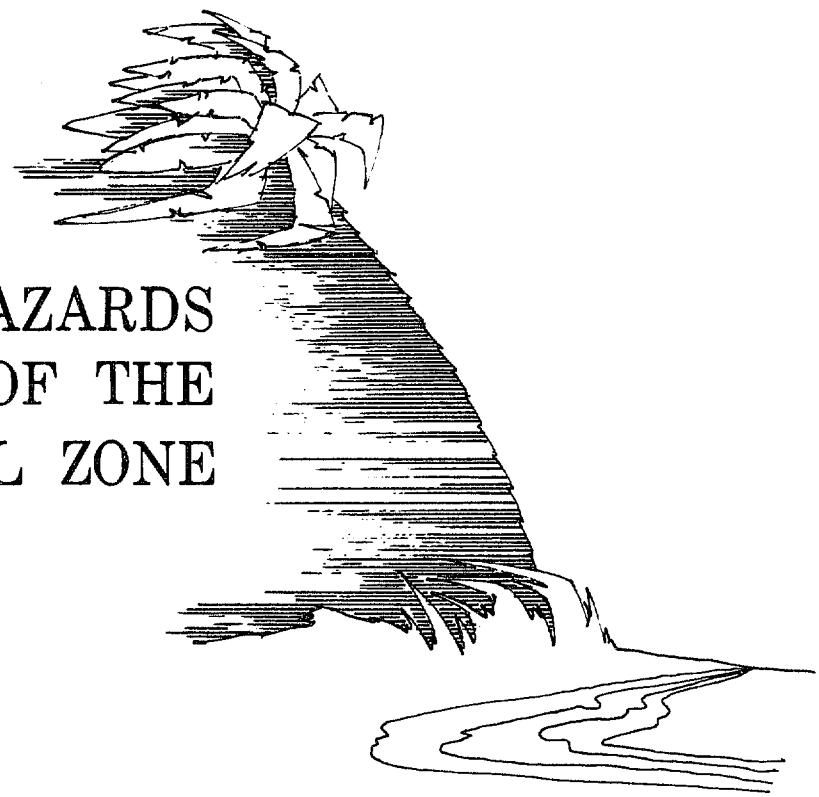
FIGURE I-3

WAVE SCOUR CAN CAUSE EXTENSIVE DAMAGE BY UNDERMINING STRUCTURES AND INADEQUATE PROTECTIVE WALLS

(Eloise. Panama City, Florida, 1975)

SECTION II

NATURAL HAZARDS OF THE TEXAS COASTAL ZONE



L. F. Brown, Jr., Robert A. Morton, Joseph H. McGowen, Charles W. Kreitler, and W. L. Fisher

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INTRODUCTION

GENERAL STATEMENT

The Texas Coastal Zone is marked by diversity in geography, resources, climate, and industry. It is richly endowed with extensive petroleum reserves, sulfur and salt, seaports, intracoastal waterways, mild climate, good water supplies, abundant wildlife, rich agricultural lands, commercial fishing resources, unusual recreational potential, and large tracts of uncrowded land. The Coastal Zone, as herein defined, is a vast area of about 18,000 square miles, including approximately 2,075 square miles of bays and estuaries, 367 miles of Gulf coastline, and 1,100 miles of bay, estuary, and lagoon shoreline (table 1). About a quarter of the State's population and a third of its economic resources are concentrated in the Coastal Zone, an area including about 6 percent of the total area of the State.

Table 1. Statistical information for the area covered by the Natural Hazards Maps. All data by Texas Bureau of Economic Geology, except areas of Hurricanes *Carla* and *Beulah* salt-water flooding and areas of *Beulah* rainfall flooding. After U. S. Army Corps of Engineers (1962, 1968).

Number of hurricane landfalls, 1900-1972	27
Area (square miles) of salt-water flooding, Hurricanes *Carla* and *Beulah*	3,164
Area (square miles) of fresh-water flooding, Hurricane *Beulah*	2,187
Area (square miles) of fresh-water flooding by hurricane rainfall (floodplains), northern part of Coastal Zone only	2,073
Area (square miles) below elevation of 20 feet (MSL): subject to salt-water flooding by tidal surge	5,787
Number of active or potential hurricane washover channels	137
Number of miles of Gulf beach erosion: greater than 10 feet per year (long term)	47
Number of miles of Gulf beach erosion: from 5 to 10 feet per year (long term)	50
Number of miles of Gulf beach erosion: from 0 to 5 feet per year (long term)	104
Number of miles of bay and lagoon shoreline erosion	408
Area (square miles) of land subsidence: greater than 5 feet	227
Area (square miles) of land subsidence: from 1 to 5 feet	1,080
Area (square miles) of land subsidence: from 0.2 to 1 foot	5,422
Number of miles of known active surface faults	96
Number of miles of Gulf shoreline	367
Number of miles of bay-lagoon shoreline	1,100
Area (square miles) of bays and lagoons	2,075
Area (square miles) of land in map area	18,000

The Texas shoreline is characterized by interconnecting natural waterways, restricted bays, lagoons, and estuaries, low to moderate fresh-water inflow, long and narrow barrier islands, and extremely low astronomical tidal range. Combined with these natural coastal environments are bayside and intrabay oil fields, bayside refineries and petrochemical plants, dredged intracoastal canals and channels, and satellite industries. Exploration and development of offshore oil and gas resources are also under way.

The Texas Coastal Zone has become an attractive area for industrialization, urbanization, and recreational development. The zone is characterized by a variety of dynamic natural physical, biological, and chemical processes. Of critical concern to Texans, however, are those natural processes which constitute hazards, both to property and life in the Texas Coastal Zone. This atlas is dedicated to a better understanding of these natural hazards, their processes, impact, and possible mitigation.

Texas is subjected to a diversity of natural hazards, most of which impact upon the dynamic Coastal Zone and immediately adjacent inland areas. Principal among these natural hazards are (1) shoreline erosion, (2) land-surface subsidence, especially in the upper Coastal Zone, (3) frequent and damaging hurricanes, (4) flooding from streams and hurricane-tidal surges, and (5) active surface faulting. Each of these hazards results in substantial physical and monetary losses; hazards such as flooding and hurricane impact also have resulted in the loss of many lives. In addition, the areal extent of certain of the hazards, such as subsidence and active faulting, is increasing in size each year. In all cases, more extensive development in the Coastal Zone means that there will be greater impact from natural hazards in the future unless adequate mitigation is undertaken.

The most effective and, in some cases, the only mitigation of natural hazards and resulting damage is to avoid certain uses of hazard-prone lands. Mitigation by selected use requires, however, that the extent, frequency, and impact of natural hazards be known. The basic goal of this atlas, "Natural Hazards of the Texas Coastal Zone," is identification of the principal natural hazards of the Coastal Zone (fig. 1), delineation of hazard occurrence and distribution, recognition of the natural and man-induced causes of these hazards, and evaluation of measures that may lead to mitigation of hazard impact.

The Bureau of Economic Geology, The University of Texas at Austin, has conducted a variety of research programs in the Texas Coastal Zone. The primary program has been the preparation of an extensive "Environmental Geologic Atlas of the Texas Coastal Zone." The Environmental Geologic Atlas is a

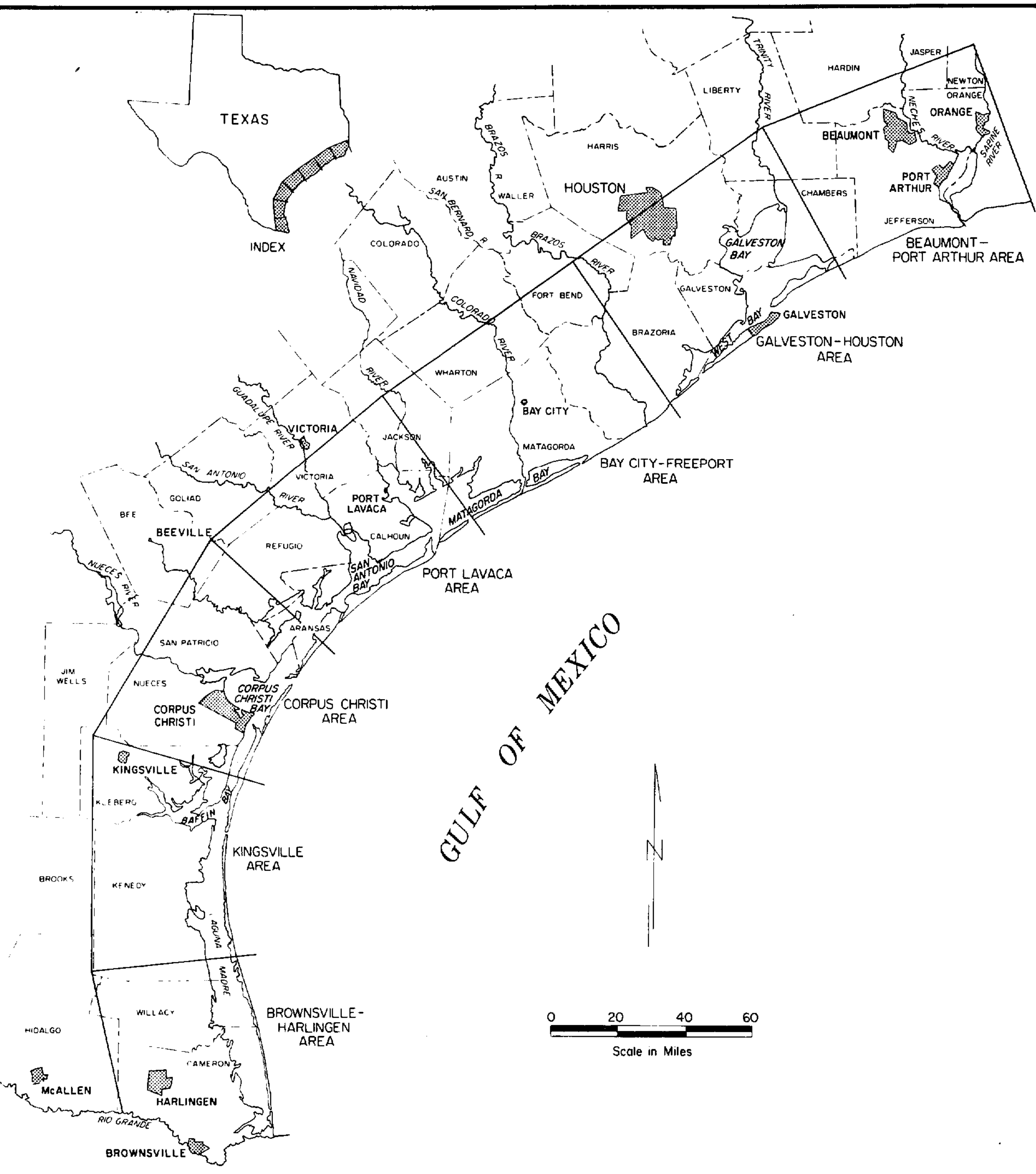


Figure 1. Index of Natural Hazards Maps of the Texas Coastal Zone.

series of seven individual atlases designed to provide a comprehensive inventory of the land, water, and natural resources of the Texas Coastal Zone. Further, the 63d Legislature of the State of Texas, through a special line appropriation, directed the Bureau of Economic Geology to conduct a program involving the historical monitoring of the Texas Gulf shoreline. By mapping the shoreline position at selected historical intervals using available, controlled aerial photographs and coastal charts, along with surveyed beach profiles, the historical rate of change of the Gulf shoreline and related natural features has been determined. Recognition of the major natural hazards of the Coastal Zone and consequent impact was an outgrowth of these investigations of shoreline change, as well as the result of mapping and analysis as a part of the "Environmental Geologic Atlas of the Texas Coastal Zone." Various natural hazards in the Texas Coastal Zone have been evaluated in a number of reports already published or currently in preparation. This report is intended primarily to summarize in a general way the current knowledge of the distribution, nature, and impact of these natural coastal hazards.

NATURAL HAZARDS AND LAND USE

The subject of land use, and especially any consideration of land-use management, is complex. In the case of lands subjected to hazardous coastal processes, however, the application of any measures, whether voluntary or obligatory, structural or nonstructural, that lead to the reduction and mitigation of damage caused by these natural hazards, is beneficial. Nevertheless, a number of problems are involved in proper mitigation. First, an adequate effort must be expended in delineating hazard-prone lands and in determining the economic impact of selected use of hazard-prone lands. Second, the economic incentive for mitigation is largely negative; it is unlike the positive incentives for the effective management of agricultural lands. Finally, the kinds of cost-to-benefit ratios involved for various, specific uses of hazard-prone lands must be determined. In some cases, damages and losses sustained in utilizing certain hazard-prone lands may be offset by significant economic gain. For example, the agricultural use of floodplains may result in periodic crop damage and loss by flooding, but the overall high yield from these fertile lands justifies their continued use. Clearly, a different cost-to-benefit ratio exists in the use of floodplains for residential development. In another example, the use of ground water in the Coastal Zone results in substantial annual savings over the cost of transport and treatment of surface water. The withdrawal of ground water, however, causes subsidence and some associated problems which result in property damage and land loss. Natural hazards and measures for reduction of losses should be considered logically in the context of both costs and benefits for specific uses of hazard-prone lands.

NATURAL HAZARDS OF THE TEXAS COASTAL ZONE

Natural hazards in the Texas Coastal Zone and immediately adjacent land areas can be classified into two general categories. Some of these hazards are dynamic, relatively *short-term* events, such as hurricanes and flooding; the more obvious impacts are known, even if not always fully respected. Other hazards, such as shoreline erosion, land-surface subsidence, and active surface faulting, are relatively *long-term* processes; they are commonly less dramatic and, for the most part, are neither widely recognized nor appreciated.

In this atlas, natural hazards are discussed in terms of distribution and occurrence, processes and causes, impacts, and mitigation and reduction. This text, as well as the figures and tables, is intended to provide a perspective which will enable the reader to better understand and interpret the maps of the atlas. Inclusion of areas of coastal hazards, except for the flood-prone areas of the upper Texas Coastal Zone, is based on actual, recent occurrences that have been observed, monitored, or measured. The hazards are defined on the basis of data available in 1974; additional information in the future certainly may permit improvement of the accuracy of the maps.

The seven maps of the atlas (fig. 1) each contain a descriptive legend, as well as other conventional map symbols. The base map was constructed from 350 U. S. Geological Survey 7.5-minute quadrangle maps by the cartography section of the Bureau of Economic Geology. The scale of the maps is 1:250,000 or 4 miles per inch. Sources of map data, as well as credits, are listed in the legend of each map and are further documented in the following text. Although this atlas is the collective product of the listed writers, each individual writer assumed principal responsibility for preparation of one or more sections: Introduction and Conclusions—W. L. Fisher and L. F. Brown, Jr.; Hurricanes—J. H. McGowen; Flooding—L. F. Brown, Jr.; Shoreline Erosion—R. A. Morton; Land-Surface Subsidence—W. L. Fisher; and Faulting—C. W. Kreitler.

Information and data for several of the natural hazards reported herein are available in more detailed form and on more detailed base maps; these sources are cited in this report. In addition, more detailed information on shoreline erosion exists on work maps on file at the Bureau of Economic Geology.

ACKNOWLEDGMENTS

Many staff members of the Bureau of Economic Geology contributed to the preparation of this report. Cartographic preparation of the maps was by R. L. Dillon, Barbara Hartmann, and D. F. Scranton under the direction of J. W. Macon, chief cartographer. Research assistance was provided by the following staff members: M. Amdurer, J. L. Brewton, C. L. Burton, A. C. Funk, M. K. Pieper, and P. M. Walters. The manuscript was typed by Sharon E. Polensky and Jamie L. Tillerson. The report was edited by Kelley Kennedy, Elizabeth T. Moore, Leslie Jones, and Karen M. White. Camera-ready copy was prepared by Fannie M. Sellingsloh and Dawn M. Weiler.

The manuscript was reviewed by E. G. Wermund and M. K. Pieper, Bureau of Economic Geology; R. O. Kehle, Department of Geological Sciences, The University of Texas at Austin; and J. C. Moseley, Executive Director, Texas Coastal and Marine Council.

● HURRICANES ●

GENERAL STATEMENT

Hurricane approach and landfall may drastically change the shoreline and damage or destroy man-made structures. Large, steep waves riding the crest of a storm surge erode beaches, dunes, and cliffed bay shores and destroy inadequately designed buildings. The storm surge inundates low-lying areas along Gulf and mainland shorelines with salt water, and severe storm-surge flooding may destroy large areas of natural vegetation and agricultural crops. Fresh-water flooding produced by torrential hurricane rainfall may be particularly destructive along natural drainage systems. Hurricane winds may damage or destroy man-made structures, with mobile homes particularly vulnerable to wind damage. Because of the direct and pervasive relationship of hurricanes and many natural coastal hazards, an understanding of hurricanes is important.

DEVELOPMENT OF TROPICAL CYCLONES

A hurricane is a storm of tropical origin with a cyclonic wind circulation of 74 miles per hour or higher (Dunn and Miller, 1964). The cyclonic atmospheric system is characterized by decreasing barometric pressure toward the center and by surface winds. In the northern hemisphere, these surface winds spiral counterclockwise upward, lifting the air and eventually producing clouds and precipitation.

The hurricane is the devastating end member of the tropical cyclone class of storms. The classification that is commonly used in the Atlantic region (table 2) is as follows: (1) *tropical disturbance*—rotary circulation slight or absent on the surface; no closed isobars (contours of equal pressure) or strong winds; common throughout the tropics; (2) *tropical depression*—one or more closed isobars; wind equal to or less than Beaufort 7; (3) *tropical storm*—closed isobars; wind greater than Beaufort 7 but less than 12; and (4) *hurricane*—wind force of Beaufort 12, or 74 mph or greater.

The precise details of physical processes that produce hurricanes are not well understood. It is known, nevertheless, that the mechanism producing hurricanes must supply (1) low-level atmospheric convergence of sufficient strength to lift the moist layer; (2) high-level atmospheric divergence to remove accumulated air and yield a pressure drop at the surface; and (3) energy to maintain the atmospheric circulation.

Conditions favorable for tropical cyclone development exist in the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico from June through October (fig. 2). Tropical storms and hurricanes that strike the Texas Coast occur most frequently in August and September (fig. 3). The mean storm track and the area of most frequent origin change from month to month during the hurricane season. Storms spawned at a particular time and place have a preferred landfall area (Dunn and Miller, 1964). The most frequent landfall area for storms that develop in the northwestern Caribbean or the Gulf of Mexico in June is the Texas Coast. The Texas Coast is rarely struck by hurricanes after the middle of September.

Table 2. Beaufort scale of wind force. After Dunn and Miller (1964).

Beaufort No.	MPH	Knots	U. S. Weather Bureau Classification
0	1	1	Light
1	1-3	1-3	
2	4-7	4-6	
3	8-12	7-10	Gentle
4	13-18	11-16	Moderate
5	19-24	17-21	Fresh
6	25-31	22-27	Strong
7	32-38	28-33	
8	39-46	34-40	Gale
9	47-54	41-47	
10	55-63	48-55	Whole Gale
11	64-73	56-63	
12	74 or >74	64 or >64	Hurricane

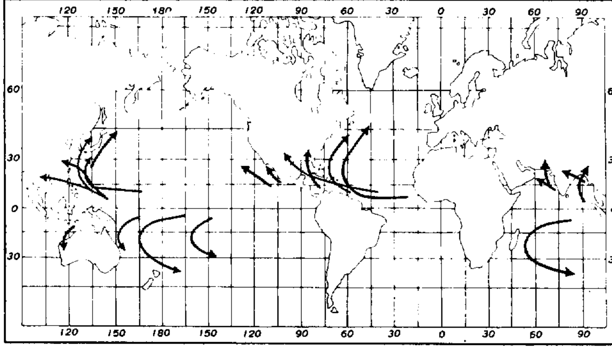


Figure 2. Areas of tropical cyclone development. After Dunn and Miller (1964).

hurricane vortex. The Intertropical Convergence Zone is the area where winds from the North and South Atlantic converge. When the ICZ moves north or south of the equator, the Earth's rotation imparts a spin to converging currents, thereby developing tropical cyclones. In the North Atlantic this occurs near Cape Verde. A polar trough is a low-pressure zone which migrates from west to east within the prevailing westerlies. The westerlies lie north of the Azores-Bermuda High. When the polar trough is very strong or when the Azores-Bermuda High is weak, the trough may penetrate the tropics. Its influence on the development of tropical cyclones is greatest either early or late in the hurricane season.

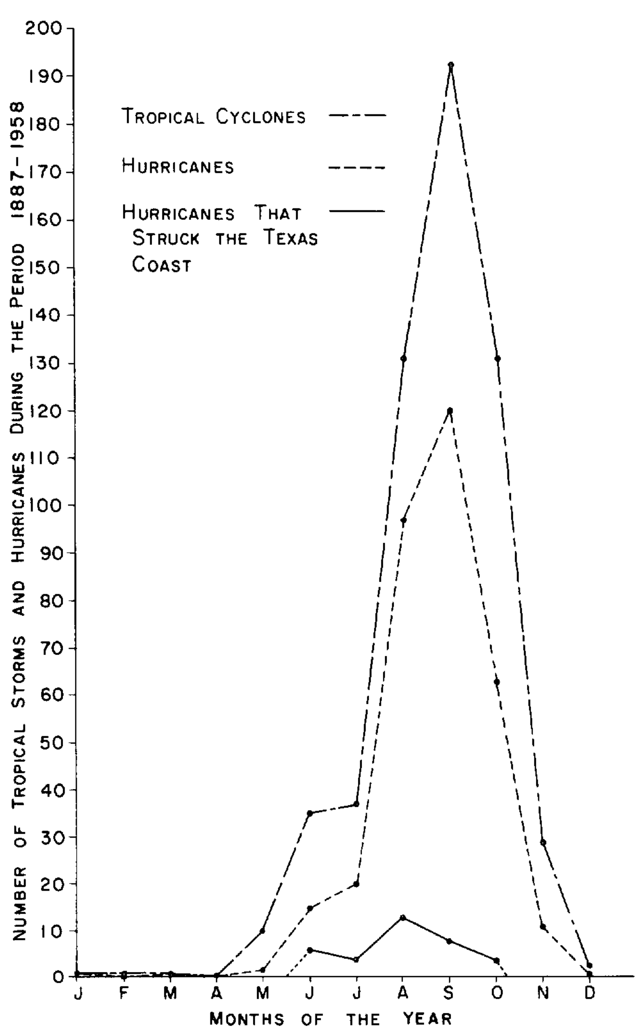


Figure 3. Frequency of Atlantic tropical cyclones and hurricanes and the number of hurricanes that struck the Texas Coast between 1887 and 1958. Data from Dunn and Miller (1964).

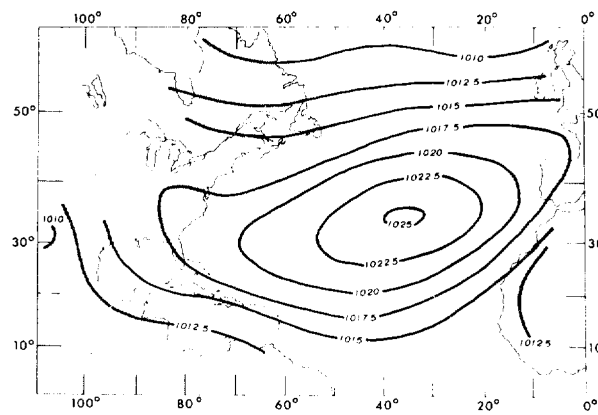


Figure 4. Mean position of the Azores-Bermuda High during the month of August. Mean sea-level pressure in millibars. After Dunn and Miller (1964).

Atmospheric conditions or elements that directly or indirectly contribute to the formation of tropical cyclones are (1) the Azores-Bermuda High, (2) easterly waves, (3) the Intertropical Convergence Zone, and (4) polar troughs. The Azores-Bermuda High is a large anticyclone extending from the Iberian Peninsula to the southeastern United States (fig. 4). It is the dominant atmospheric system for the Atlantic during summer and early fall when the High oscillates from north to south (Dunn and Miller, 1964). Persistent departures from normal position have a significant effect on hurricane frequency and paths. The easterly wave is a low-pressure trough which is imbedded in the easterly current lying south of the Azores-Bermuda High. A stable wave may move from east to west as much as 3,000 miles without any change. Deviation from the norm indicates that the wave is developing a

A hurricane runs on heat. Its formation and maintenance depend upon energy derived from the ocean surface. Hurricanes form over comparatively warm water with a temperature above 79°F. Warm moist air moves across the ocean surface spiraling inward into the hurricane circulation. As it rises to higher elevations, it expands under reduced pressure. When the air becomes saturated, moisture condenses and releases heat to the surrounding atmosphere. Energy is partly dissipated in the upper anticyclonic flow by surface and internal friction.

CHARACTERISTICS OF HURRICANES

The principal features of a hurricane are (1) the eye, surrounded by convective clouds; (2) low-level cyclonic winds; (3) upper level anticyclonic winds; and (4) a vertical circulation system in which air flows into the eye at low levels, flowing upward within the convective clouds, outward in the upper levels, and downward in the outer parts of the storm (fig. 5).

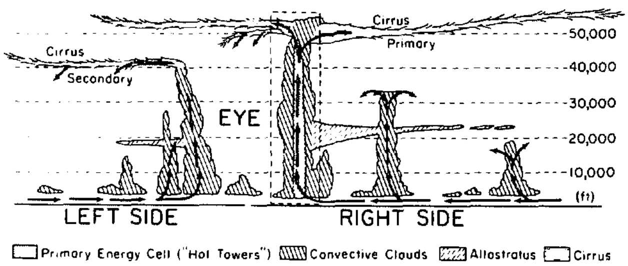


Figure 5. Hurricane model. The primary energy cell (convective chimney) is located in the area enclosed by the broken line. After Carr (1967).

The eye of the hurricane is a low-pressure area where wind velocities are only 10 to 20 mph. The eye may be relatively small, only 4 miles in diameter, or large, up to 25 miles in diameter. Average diameter is about 14 miles (Dunn and Miller, 1964).

Air flows from high-pressure areas toward the low-pressure storm center. The pressure differential results primarily from temperature differences. Strongest hurricane winds are near the storm center because this is the area with the steepest pressure gradient (fig. 6). Lower level winds have sustained velocities ranging from 74 to 200 mph; the velocity of gusts may exceed sustained winds by 30 to 50 percent. Winds are stronger on the right side of the hurricane eye (fig. 5) because the forward motion of the storm is added to the rotational wind velocities.

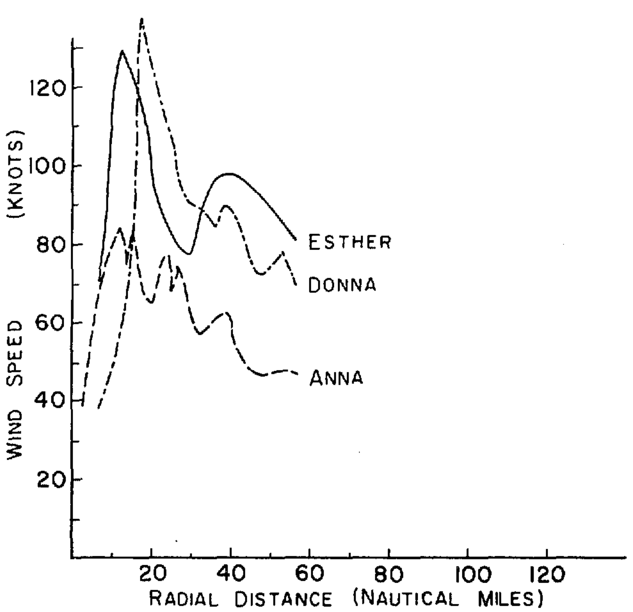


Figure 6. Wind profiles in Hurricanes *Donna*, 1960, *Esther*, 1961, and *Anna*, 1961. After Colón (1966).

Table 3. Hurricane classification. After Dunn and Miller (1964).

Classification	Maximum winds (mph)	Minimum central pressure (inches Hg)
Minor	Less than 74	More than 29.40
Minimal	74 to 100	29.03 to 29.40
Major	101 to 135	28.01 to 29.00
Extreme	136 and higher	28.00 or less

Table 4. The nature of hurricanes striking the Texas Coast between 1900 and 1972. Dash indicates that data are unavailable. Data from National Oceanic and Atmospheric Administration—National Hurricane Center (1900-1974). Note that data do not necessarily agree with that provided by U. S. Army Corps of Engineers (1962, 1968, 1971a).

Hurricane	Date & location of landfall	Approach speed	Wind velocity maximum	Pressure at eye	Storm surge height	Dollar value of damage	Deaths
1900 Not named	Sept. 8 Galveston	10 mph	125 mph	27.64"	20' Galveston	$30,000,000	6,000
1909 Not named	July 21 Velasco	12 mph	120 mph	29.00"	10' Galveston	$2,000,000	41
1910 Not named	Sept. 14 Padre Island (south)		120 mph	-		minimal	
1912 Not named	Oct. 15 Mustang Island	-	100 mph		-	$28,000	
1913 Not named	June 27 Padre Island (central)	-	100 mph		12.7' Galveston		
1915 Not named	Aug. 17 Freeport	11 mph	120 mph	28.06"	16' Galveston Causeway	$50,000,000	275
1916 Not named	Aug. 18 Padre Island (nor	11 mph	130 mph	28.00"	9.2' Central Padre	$1,800,000	20
1919 Not named	Sept. 14 Corpus Christi	10 mph	120 mph	27.99"	16' Corpus	$20,270,000	300-600
1921 Not named	June 22 Port O'Connor	-	110 mph	-	7.1' Pass Cavallo	minimal	
1929 Not named	June 28 Port O'Connor	17 mph	90 mph	28.62"	3' Port O'Connor	$675,000	3
1932 Not named	Aug. 13 Freeport	17 mph	110 mph	27.83"	6.1' Freeport	$7,500,000	40
1933 Not named	Sept. 4-5 Brownsville	8 mph	100 mph	28.02"	13' [illegible]	$12,000,000	40
1934 Not named	July 25 Rockport	-	70 mph		10.2' St. Joseph Island	$4,500,000	11
1936 Not named	June 27 Port Aransas		80 mph	-		$550,000	
1940 Not named	Aug. 7 Port Arthur	8 mph	80 mph	28.87"	2.1' Sabine Pass, High Island	$1,750,000	-
1941 Not named	Sept. 23 Freeport	13 mph	90 mph	28.31"	9.9' Sargent	$6,000,000	4
1942 Not named	Aug. 22 Gilchrist	-	72 mph	29.35"	7' High Island	$601,000	0
1942 Not named	Aug. 29-30 Matagorda Bay	14 mph	110 mph	28.10"	14.7' Matagorda	$26,500,000	8
1943 Not named	July 27 Port Bolivar	9 mph	100 mph	28.78"	3' Port Bolivar	$16,550,000	19
1945 Not named	Aug. 27 Matagorda Bay	4 mph	130 mph	28.57"	15' Port Lavaca	$20,133,000	3
1947 Not named	Aug. 24 Galveston	-	80 mph	29.30"	3.6' Sabine Pass	$200,000	1
1949 Not named	Oct. 3 Freeport	13 mph	135 mph	28.88"	11.0' Freeport	$6,700,000 mainly crops	2
1959 Debra	July 25 Galveston	6 mph	80 mph	29.07"	2.8' Galveston	$7,000,000	0
1961 Carla	Sept. 11 Port O'Connor	6 mph	150 mph	27.49"	22' Port Lavaca	$408,000,000	46
1963 Cindy	Sept. 17 High Island	8 mph	60 mph	29.41"	4.2' High Island	$11,700,000 incl. Louisiana	3
1967 Beulah	Sept. 20 E. of Brownsville	8 mph	140 mph	27.98"	12' Port Isabel	$200,000,000	15
1970 Celia	Aug. 3 Corpus Christi	-	130 mph	27.80"	9.2' Port Aransas	$453,000,000	11
1971 Fern	Sept. 10 Between Freeport and Matagorda	-	78 mph	29.04"	6' Freeport	$30,000,000	2

Hurricane size is commonly expressed in terms of diameter of hurricane and gale winds or by diameter of the outer closed isobar. Average diameters of hurricane and gale winds are about 100 and 400 miles, respectively. There is a wide range in the size of hurricanes. The Great Atlantic Hurricane of 1944 had hurricane winds with a diameter of 600 miles (Dunn and Miller, 1964). Hurricane *Carla*, in 1961, had hurricane-force winds with a diameter of about 300 miles (Colón, 1966; Hayes, 1967), and in 1970, *Celia's* hurricane wind diameter was about 80 miles.

Hurricane size and intensity are not directly related. The most intense hurricanes are not necessarily the largest; for example, the diameter of cyclonic circulation tends to increase during the decaying stage (Colón, 1966). Low barometric pressure and relatively high wind velocity are common to all tropical disturbances (table 3), and these parameters are more suitable for classifying hurricanes (Dunn and Miller, 1964).

Average life of a hurricane, determined by time and place of origin and rate of forward movement, is about nine days. Most hurricanes move forward at a rate of about 12 mph. The forward speed of hurricanes that have struck the Texas Coast in August and September has averaged 8 to 12 mph. Hurricanes that struck the Texas Coast between 1900 and 1972 exhibit a wide variety of characteristics (table 4).

RELATED STORM EFFECTS

Hurricanes produce striking changes in the sea; huge waves and storm tides are generated. Hurricanes also trigger heavy rainfall, create high-velocity winds, and spawn tornadoes. As the storm approaches and makes landfall, each of these related phenomena becomes increasingly more important because hurricanes have the potential to alter the shoreline by erosion or deposition, to flood low-lying areas, and to damage or destroy man-made structures.

Changes in Water Level

A slow rise in water level occurs when oceanic swells generated by a distant storm approach the coast. This rise in water level is known as the *forerunner*. A rise in water level of 3 to 4 feet, produced by the forerunner, can affect several hundred miles of coast (Dunn and Miller, 1964). *Storm surge*, on the other hand, is a rapid rise in water level generated by onshore hurricane winds and decreasing barometric pressure. Maximum storm surge generally occurs 10 to 20 miles to the right of the storm track, but it may occur to the left of the storm if counterclockwise north winds stack water against an obstruction, such as the back side of a barrier island.

Waves

Principal damage to man-made structures and severe erosion of shorelines are produced by storm waves superimposed on the storm surge. The power generated by a breaking wave can be visualized by considering that a cubic yard of water weighs about 1,500 pounds and that waves may be moving at a velocity of about 70 to 80 feet per second. Breaking waves alone can destroy many buildings, but their destructive potential is significantly increased by tree trunks, pilings, and other debris that act as battering rams. Appropriately designed structures, nevertheless, can withstand flooding associated with the forerunner and storm surge.

The shoreline may retreat several hundred feet during a few hours when under attack by storm waves (Shepard, 1973; McGowen and Brewton, 1975). Between hurricanes, accretion may restore much of the shoreline lost during the storm.

Maximum surge height is commonly associated with a storm which has a track perpendicular to the shoreline. It is also greatest along coasts, such as the Texas Gulf Coast, that are concave and adjacent to wide, gently sloping shelves. If the hurricane landfall coincides with the astronomical high tide, surge height will be even greater.

The rare "hurricane wave" or seiche has caused some of the world's greatest natural disasters (Dunn and Miller, 1964). It may result from resonance that produces a huge wave, or it may be a rapidly rising and abnormally high storm surge. The hurricane that struck Galveston on 8 September 1900 may have been accompanied by such a hurricane wave. During the Galveston storm, water level rose steadily from 3:00 to 7:30 p.m., at which time there was an abrupt rise of about 4 feet in as many seconds (Dunn and Miller, 1964).

Development of Washover (Breach) Channels

One of the principal effects of the storm surge is the development of washover channels that breach barrier islands or peninsulas. These channels readily develop at the sites of eolian erosion (blowouts) or in areas with poorly developed fore-island dune ridges and beach ridges. Tidal waters flow landward through the channels, scouring sand and depositing the sediment in washover fans within the adjacent bay or lagoon. Following passage of the hurricane, the channels serve to return the elevated waters of the bays and lagoons to the open Gulf. The surge channels are active only during the brief period of hurricane approach, landfall, and immediate aftermath; storms tend to reactivate the same washover channels. Marine shoreline processes close the gulfward end of the channel within a few days. Water may stand in the abandoned channel for months following the storm.

In general, the density of washover channels increases southwestward along the Texas Coast. This regional increase in channels results principally from the southwestward decrease in vegetational stability of barrier islands and fore-island dunes. A total of 137 washover channel sites have been recognized and are shown on the Natural Hazards Maps. The location of these sites is based on interpretation of aerial photographs, low-level aerial reconnaissance, and field work undertaken as part of the "Environmental Geologic Atlas of the Texas Coastal Zone." Construction within or immediately adjacent to hurricane breach or surge channels may lead to property damage in the event of a hurricane landfall.

Rainfall

Some of the greatest rainfalls recorded in Texas have resulted from hurricanes. Upon striking a landmass and moving inland, the forward movement of a hurricane is reduced, and the rate of rainfall increases. Maximum rainfall occurs in front of and along the right side of slowly moving tropical storms. Rainfall is equally distributed in the front and rear halves of storms whose forward motion has stalled.

Wind

Hurricane winds rank third behind waves and rainfall flooding in destructive potential. Width of the area of destructive winds may range from about 14 to 300 miles (Dunn and Miller, 1964). Wind velocities of 100 to 135 mph are common. Severe storms have velocities of 135 to 160 mph; the most violent hurricanes have wind velocities of 200 mph or greater. Damage to structures results from sudden pressure changes associated with gusts. Damage begins when pressure reaches approximately 15 to 20 pounds per square foot (wind velocity of about 60 mph).

The highest velocity winds associated with hurricanes are contained in tornadoes having estimated velocities of 400 to 500 mph. Tornadoes may occur at any time during and immediately following hurricane passage; their most frequent occurrence is in the forward half of the storm.

GENERALIZED HURRICANE MODEL

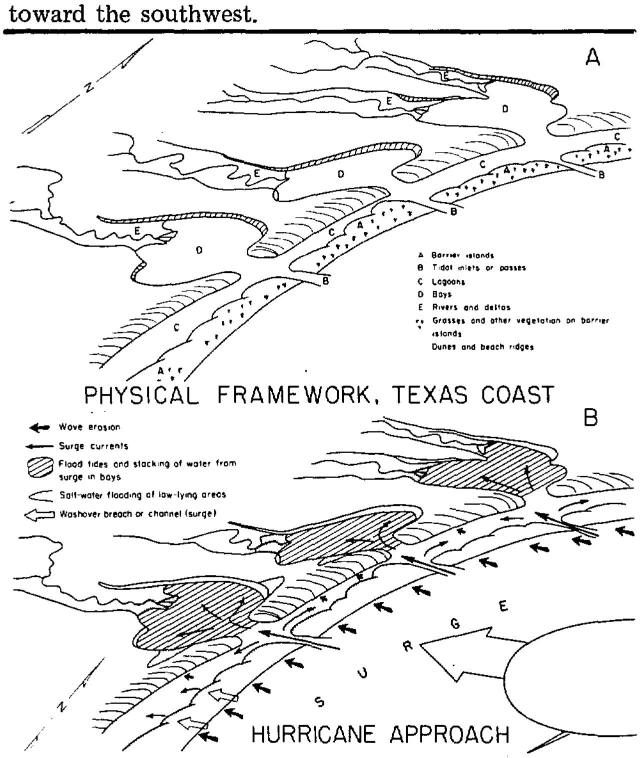
Historical records indicate that successive hurricanes may differ markedly (table 4). One hurricane may generate a large storm surge, another may be characterized by torrential rainfall, while exceptionally high wind velocities may define a third type. From these records and from previous studies, a general hurricane model (fig. 7) was developed (Price, 1956; Hayes, 1967; McGowen and others, 1970). The following is a description of a model hurricane as it approaches the Texas Coast, makes landfall, and moves inland.

Storm Approach

Storm approach (fig. 7B) is marked by rising tides (forerunners) and increased wind velocities. When the storm strikes the coast, the storm surge and associated waves erode the normal beach and foredunes to form a broad, flat hurricane beach. Storm-surge flooding often scours washover channels across barrier islands and peninsulas. Sediment is transported through the storm channels and is deposited on barrier flats and along bay margins as washover fans. Mainland shorelines receive muddy sediment that is derived from the bay bottom and carried ashore by storm-surge floods. Storm-surge tides are commonly higher in the bays than on the Gulf beaches, although the flooding and the effects of the accompanying waves are pronounced in both areas.

Landfall

At landfall (fig. 7C), when the storm passes over the shoreline, the direction of current movement and wave approach shifts into compliance with the change in wind direction. Highest intensity winds are felt as the storm comes ashore. On the left side of the storm, water and sediment are moved from the bays back into the Gulf through inlets and breaches in the island, while water and sediment are still being pushed into the bays on the right side. Waves strike the Gulf shoreline at a low angle as the back side of the storm passes, creating currents that transport sediment northeastward alongshore in the same manner that the front-edge winds and currents had moved materials toward the southwest.



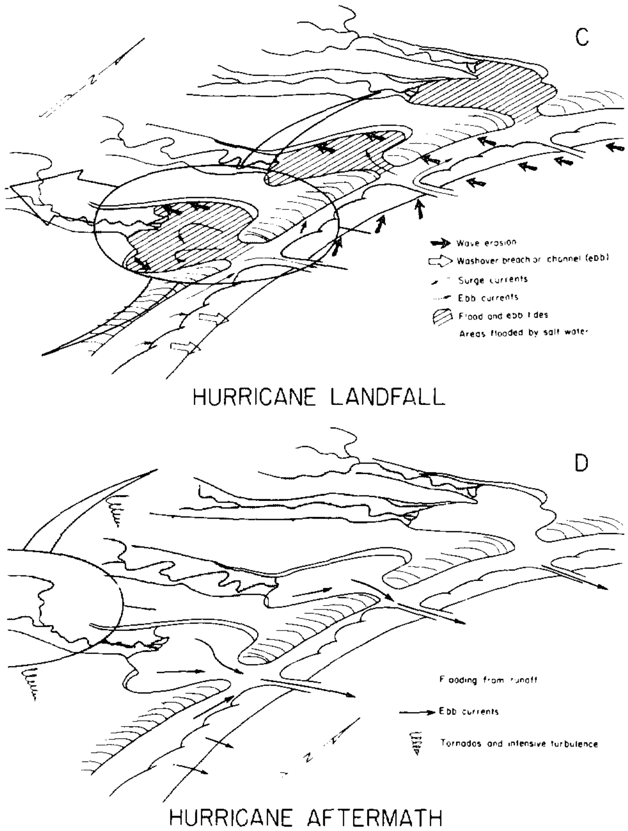


Figure 7. Schematic model of hurricane effects on the Texas coastline. (A) Physical features characterizing the Texas Coast, (B) Effect of approaching hurricanes, (C) Effect of hurricanes upon impact with coast, (D) Aftermath effects of hurricanes. After McGowen and others (1970).

Hurricane Aftermath

Hurricane aftermath (fig. 7D) is the period following passage of the storm inland from the coastal area. As the storm moves inland, it becomes weaker and more diffuse, and commonly spawns numerous tornadoes. Excessive water in the bays drains gulfward through storm breach channels and passes, depositing sediment within the channels and in the nearshore Gulf. Heavy rains that commonly accompany hurricanes produce runoff of flood proportion, inundating low-lying areas along stream courses and bay margins. The influence of strong winds and heavy rains may accompany the storm inland for considerable distances.

Longshore currents begin to build bars that eventually close off the mouths of hurricane channels, and waves begin to restore the normal beach profile. Hurricane deposits are reworked by subsequent rains and wind. Some of the sand that is exposed in breach channels is blown landward onto the barrier fla+, and washover fans are reworked by bay and lagoon waves and currents.

TYPES OF HURRICANES

During the past 70 years, most coastal areas in Texas have experienced severe weather resulting from direct impact or nearby passage of a hurricane. No area, however, has experienced each of the hurricane types which can strike during the hurricane season. Using meteorological and hurricane data accumulated over the past several decades, it is possible to recognize at least three general kinds of hurricanes and to predict their impact on different parts of the Texas Coast (table 4). Predictability of hurricane effects is based on (1) bay-estuary shape, (2) Gulf shoreline configuration, (3) track of the hurricane relative to the coastline, (4) nature and distribution of physical and biological environments, and (5) population density. Three recent, well-documented hurricanes, *Carla*, *Beulah*, and *Celia*, illustrate the nature of hurricane variations (table 5; fig. 8). The reader should be aware that observations such as storm-surge elevation, hurricane wind velocity, and pressure values, may vary among observers. For this reason, the sources of the data are noted in this atlas; any inconsistencies in wind velocity or storm surge, for example, result from the use of several data sources.

Hurricane *Carla*

Hurricane *Carla* was spawned in the western Caribbean on or about 3 September 1961. She became a hurricane on 5 September and moved into the Gulf of Mexico between Cuba and the Yucatan Peninsula on 7 September (Hayes, 1967). *Carla* moved toward the Texas Coast at about 9 mph, making landfall (fig. 8) near Port O'Connor on 11 September (Port Lavaca map). Her travel time over the warm waters of the Caribbean and Gulf of Mexico was about nine days. Maximum sustained winds at landfall were about 175 mph, and pressure in the eye was about 931 millibars

Table 5. The characteristics of basic types of hurricanes striking the Texas Coastal Zone. After McGowen and others (1970).

Variables	*Beulah* type	*Carla* type	*Celia* type
Wind	Moderate	Moderate	High
Storm-surge tides	Moderate	High	Low
Rainfall	High	Moderate	Low
Size of destructive core	Medium	Large	Small
Length of aftermath effects	Extended	Intermediate	Brief
Character of coastline affected	Port Mansfield: poorly vegetated, low relief, broad unrestricted bay	Port O'Connor: well vegetated, local relief to 30 feet, funnel-like Lavaca Bay	Port Aransas: moderate vegetation, local relief to 30 feet, funnel-like Nueces Bay

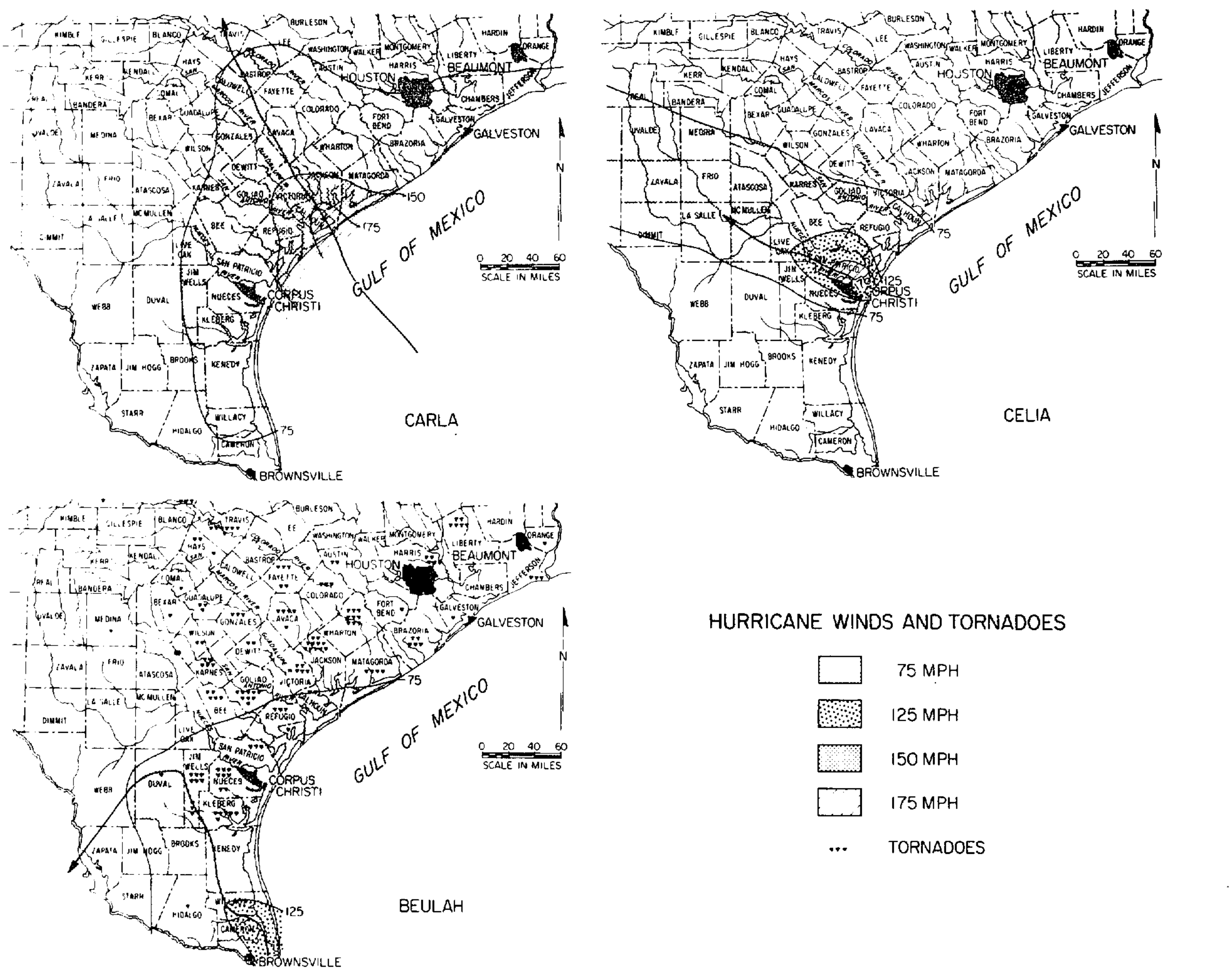


Figure 8. The track of the eyes of Hurricanes *Carla*, *Beulah*, and *Celia*, and the area covered by hurricane-level winds, Texas Coastal Zone. Based on data from Cooperman and Sumner (1961), Orton and Condon (1970), Orton (1970), and U. S. Army Corps of Engineers (1968). After Texas Coastal and Marine Council (1974).

(mb). The Galveston weather station was under effects of gale-force winds for 49 hours (Colón, 1966). Corpus Christi, only 50 to 60 miles from the storm center, experienced peak gusts of 85 mph and pressure of 977 mb. Hurricane wind diameter was approximately 300 miles (fig. 8). *Carla* was probably the largest Atlantic hurricane for which there are reliable data (Colón, 1966).

Carla was characterized by extensive storm-surge flooding (fig. 9) and severe shoreline erosion. Surge height in the Port O'Connor area was in excess of 10 feet above mean sea level (MSL), and at Port Lavaca, the surge reached a maximum of 22 feet above MSL (U. S. Army Corps of Engineers, 1962). Parts of Matagorda Peninsula were breached by storm channels, and shorelines were eroded as much as 800 feet (Shepard, 1973; McGowen and Brewton, 1975). Dunes on Mustang Island were eroded landward as much as 150 feet (Hayes, 1967).

Carla's track across the Gulf of Mexico was northwestward. After landfall, her course curved to the northeast, and she crossed the United States and entered Canada in the Great Lakes area.

Hurricane *Beulah*

Hurricane *Beulah* was spawned in the Atlantic, becoming a hurricane on 7 September 1967 (Scott and others, 1969). She moved west-northwestward into the Caribbean, lost considerable energy in the mountains of Haiti, re-formed and assumed a more westerly course crossing the Yucatan Peninsula on 17 September. She made landfall (fig. 8) in Mexico, just south of Brownsville, on 20 September (Brownsville-Harlingen map). After becoming a hurricane, her travel time over the Caribbean Sea and Gulf of Mexico was 13 days. Maximum wind velocity at landfall was 125 to 160 mph. In Texas, winds of hurricane force extended from the Rio Grande northward approx-

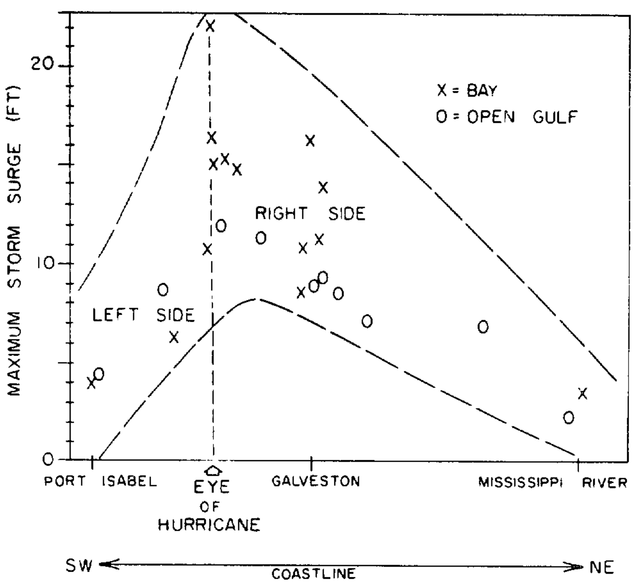


Figure 9. Maximum storm surge that occurred during Hurricane *Carla*, 1961, at 14 bay and 10 open Gulf localities along the northwest Gulf of Mexico. Note that the right side of *Carla* generated greater storm surge than the left side of the storm. Based on tide data collected by the U. S. Army Corps of Engineers, Galveston and New Orleans Districts, and presented by Cooperman and Sumner (1961) and Harris (1963). After Hayes (1967).

imately 250 miles (fig. 8). Storm surge was about 10 feet above MSL at Brazos Santiago, and tides were 6 to 7 feet between Port Mansfield and Port Aransas and 5 feet near Cedar Bayou (Behrens, 1969; Scott and others, 1969).

After making landfall, *Beulah* traveled north-northwestward inland into Duval County, changed her course to the southwest, and moved back into Mexico. The long path overland slowed the storm, resulting in heavy rainfall and the generation of at least 115 tornadoes (fig. 8). *Beulah* was characterized by exceptionally heavy rainfall; in some areas, rainfall was in excess of 30 inches during the four or five days of aftermath storms.

Hurricane *Celia*

Hurricane *Celia* was spawned in the Caribbean Sea near Cuba. A tropical squall struck the western part of Cuba on 31 July 1970. On the morning of 1 August, the disturbance became a tropical storm, and on the afternoon of 1 August, *Celia* became a hurricane (McGowen and others, 1970). *Celia's* course was west-northwest toward the Texas Coast, and her rate of forward movement was 10 to 15 mph. She made landfall at Port Aransas on 3 August (Corpus Christi map); her travel time over the Gulf of Mexico was only three days. At about the time she made landfall, the eye decreased in size by about 40 percent, and wind velocity increased from 90 to 130 mph with gusts of 160 to 180 mph. The width of *Celia's* destructive path was about 15 miles, and her hurricane winds had a diameter of about 80 miles (fig. 8). *Celia's* inland path was west-northwest to Del Rio where her progress became irregular. The storm expired in the mountains near Chihuahua, Mexico.

Celia was accompanied by high-velocity winds and a few tornadoes. Rainfall was minimal and storm surge was restricted to a very narrow zone. Maximum surge (determined from debris lines and, therefore, not indicative of stillwater level) was about 9 feet along the Gulf shore near the Aransas Pass jetties, 12 to 14 feet along the bay shore at Aransas Pass, and up to 9 feet at Corpus Christi. Surge height in the North Pass and Corpus Christi Pass areas was only 4 feet. Hurricane *Celia* was characterized by her destructive winds; storm-surge flooding and rainfall were relatively insignificant.

FACTORS INFLUENCING SEVERITY OF HURRICANE IMPACT

The severity of hurricanes can be expressed in various terms, such as damage to man-made structures, monetary losses, and loss of human life. The nature of the storm, population density, and shoreline characteristics determine the number of lives lost, the extent of shoreline erosion, and damage to or destruction of man-made structures. The nature of the storm dictates whether storm surge, fresh-water flooding, or wind will be the dominant destructive element. The loss of human life and the amount of property damage is directly affected by population density. Shoreline characteristics will either amplify or diminish some of the hurricane processes.

Nature of the Storm

Three destructive elements are associated with hurricanes. In order of decreasing destructive potential, these are (1) storm surge and attendant breaking waves, (2) fresh-water flooding, and (3) wind. Assuming a common point of landfall, *Carla*-type hurricanes have the greatest destructive potential of the three basic hurricane types, *Beulah*-type storms rank second, and *Celia*-type storms are the least destructive. A *Celia*-type storm, nevertheless, can become highly destructive when it strikes a highly developed area (table 4).

Large, intense hurricanes, which create high storm-surge flooding with attendant wave erosion, can be expected when a storm moves slowly across the ocean without being impeded by landmasses en route to the Texas shoreline (*Carla*-type hurricane). The path that a hurricane takes after making landfall, the rate of forward movement, and the topography of the landmass over which it moves have an effect on rainfall rate, which dictates the magnitude of fresh-water flooding. A long route over the ocean by a slowly moving storm significantly increases the moisture content of the storm clouds. Slow forward movement overland, coupled with considerable topographic relief, is conducive to high rainfall rates (*Beulah*-type hurricane). A hurricane that is spawned in the Gulf of Mexico and travels rapidly across the open Gulf will most likely be accompanied by high-velocity wind, minimal rainfall, and minimal storm surge. These storms are generally small, but intense (*Celia*-type hurricane).

Shoreline Characteristics

The Texas Coast is characterized by an outer Gulf shoreline and an inner bay shoreline (fig. 7A). *Gulf shorelines* exhibit three principal morphological types: (1) deltaic headlands, (2) peninsulas, and (3) barrier islands. *Bay shores* consist of a variety of shoreline types; among these are (1) relatively high cliffs, (2) low-lying marshes, (3) bayhead deltas and river valleys, and (4) areally restricted sand and shell beaches. The shoreline type determines, in many instances, the extent of storm-surge flooding and wave erosion.

Deltaic headlands occur between Sabine Pass and Bolivar Peninsula, Follets Island and Brown Cedar Cut, and the Rio Grande and Brazos Santiago Pass. The two easternmost headlands (Beaumont-Port Arthur and Bay City-Freeport maps) are morphologically similar. Physiographic subdivisions of these two headlands include (1) forebeach, (2) erosional escarpment, and (3) shell apron or ramp (fig. 10). A shell ramp, which is about 5 to 7 feet above MSL, is commonly backed by marshes with attendant lakes and tidal creeks. These low-relief shoreline features are readily breached by storm surge and adjacent marshes are commonly flooded. With the exception of part of the Modern Brazos delta, the Texas coastal headlands erode rapidly under normal sea conditions and erode excessively during storms. Incipient dunes occur along the headlands; most dunes are destroyed by storm surge and breaking waves.

The Rio Grande deltaic headland (Brownsville-Harlingen map) is characterized by sand beaches and fore-island dunes. The vegetated dunes locally are 30 feet high. Breaks in the fore-island dune ridge may be a few hundred feet to a mile wide. The storm-tidal surge commonly breaches and scours the low areas between dunes and floods the Rio Grande delta plain and adjacent lowlands. Shoreline erosion is excessive even under normal sea conditions, but under storm conditions, shorelines may retreat a few hundred feet within a few hours. Post-storm processes may accrete the shoreline to its approximate prestorm position.

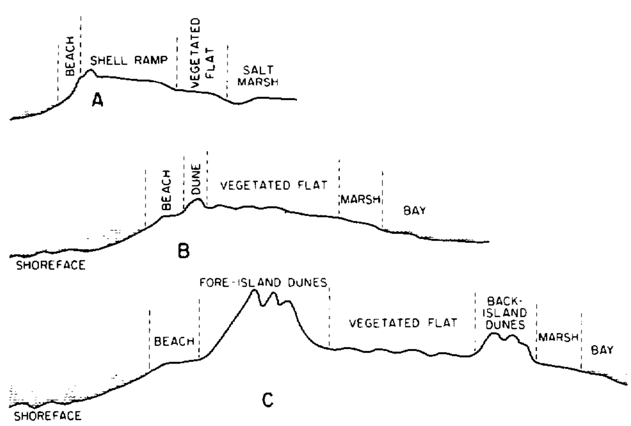


Figure 10. Generalized profiles of types of Texas Gulf Coast shorelines. (A) Headlands, (B) Peninsulas, (C) Barrier islands.

Peninsulas, which resemble offshore islands, are elongate strips of sand and shell that are attached to headlands and extend in the direction of longshore drift. Three peninsulas on the Texas Coast are Bolivar Peninsula, Matagorda Peninsula, and south Padre Island. A generalized profile across a peninsula is illustrated in figure 10.

Bolivar Peninsula (Galveston-Houston map) is about 23 miles long, is densely vegetated, and consists chiefly of fine-grained sand. It is characterized by well-developed ridge-and-swale topography, and there is no evidence of recent storm erosion or breaching of Bolivar Peninsula by storm washover channels. Maximum elevation along the seaward edge of Bolivar Peninsula is about 10 feet above MSL. Several storm-surge floods have flooded the peninsula, but dense vegetation has prevented the scouring of channels and development of active washover fans.

Matagorda Peninsula (Bay City-Freeport map) is about 51 miles long. The easternmost three miles of the peninsula is separated from the western segment by Brown Cedar Cut, a tidal pass created by a hurricane breach channel. Greens Bayou, similar to Brown Cedar Cut, is open only during and shortly following the passage of hurricanes.

The elevation of Matagorda Peninsula averages 5 to 7 feet above MSL. Continuous low dunes, 8 to 12 feet above MSL, extend from the mouth of the Colorado River eastward for about 8 miles, and from Greens Bayou westward to within a mile or two of Pass Cavallo. Storm washover channels are common along the peninsula. Spring high tides and forerunner tides associated with distant storms frequently overwash beaches adjacent to storm channels. Most of Matagorda Peninsula is overwashed by 5- to 7-foot storm surges. Continuous dunes with heights greater than about 10 feet afford some protection from storm surge.

During major storms such as Hurricane *Carla* (1961), two types of washover deposits are developed along Matagorda Peninsula: shell ramps and washover fans. Shell ramps are long berms that parallel the elongate peninsula. Individual ramps are a few miles long and 180 to 2,180 feet wide. Washover fans are lobate sand-shell bodies that accumulate at the bay terminus of storm channels that transect the peninsula. Small storm surges reactivate the channels and sometimes construct a washover fan along the bay margin. Large storms with 10 to 11 feet of storm surge cut the peninsula into numerous small islands separated by channels up to 1,700 feet wide. These same storms also may erode the shoreline as much as 800 feet (Shepard, 1973).

In South Texas, the gulfward part of the Rio Grande delta grades northward into south Padre Island (Brownsville-Harlingen map). South Padre Island, which originated as a peninsula, is now separated from the deltaic headland of the Rio Grande by Brazos Santiago Pass. South Padre Island is characterized by sand and shell beaches, sparse vegetation, and poorly developed fore-island dunes. Its morphology is the product of combined wind and storm activity. There is little natural defense to prevent breaching of south Padre Island by storms of the magnitude of *Carla* (1961) and *Beulah* (1967). Flow across the island is virtually unconfined during principal hurricanes; for example, south Padre Island was highly segmented by washover channels during Hurricane *Beulah*. Active dunes on south Padre Island range in height from 5 to 25 feet above MSL, but they present little resistance to tidal flow once a storm breach has been opened. Width of storm breach channels ranges from about 0.2 to 1.0 mile.

Barrier islands are elongate, detached sand bodies that are separated from the mainland by bays or lagoons and from each other by tidal passes. The five barrier islands of the Texas Coast are Galveston, Matagorda, St. Joseph, Mustang, and Padre. A generalized profile combining the features of Mustang Island is shown on figure 10.

Galveston Island (Galveston-Houston map) is wide and densely vegetated and is characterized by numerous sand ridges and swales. Average elevation is about 5 feet above MSL; maximum elevation of poorly developed fore-island dunes is about 15 feet above MSL. Hurricane erosion on Galveston Island is confined primarily to beaches and dunes.

Matagorda Island (Port Lavaca map) like Galveston Island is a broad, sandy island with well-defined ridge-and-swale topography and more or less continuous fore-island dunes (Wilkinson, 1974). Average elevation is about 5 feet above MSL. Fore-island dunes on Matagorda Island average about 10 feet with some peaks up to 30 feet above MSL. In historical times, hurricanes have not scoured washover channels across the island, but because of the development of several blowouts during the past few decades, breaching may occur in the near future.

St. Joseph Island (Corpus Christi map) also displays prominent ridge-and-swale topography. Vegetation on the island is less dense, and blowouts are more numerous than on islands to the east. Average elevation of St. Joseph Island is slightly more than 5 feet above MSL. Vegetated fore-island dunes average about 15 feet above MSL; there are some dunes that extend to 35 feet above MSL. Active washover channels occur at the extreme northeastern and southwestern ends of the island (Price, 1956; Andrews, 1970; Nordquist, 1972). North Pass was formed by a major hurricane in 1919 (Price, 1956; Nordquist, 1972). Approximately 9.3 million cubic yards of sediment accumulated along the bayward terminus of the washover channel as a consequence of hurricane activity, beginning with the 1919 hurricane and continuing through 1971.

Mustang Island (Corpus Christi map) is a broad barrier which has an average elevation of about 7 feet. It does not display ridge-and-swale topography. Vegetated fore-island dunes have an average elevation of about 15 feet above MSL and a maximum elevation of about 50 feet above MSL. Vegetation is less dense on Mustang than on islands to the northeast; consequently, blowouts, hurricane breaches, and washover channels are more numerous. Two factors contribute to the increased frequency of storm channel breaching on southern Mustang Island. First, there is a southwestward decrease in vegetation along the Texas Gulf Coast, and consequently, fore-island dunes are more susceptible to blowouts by wind erosion. Second, a major tidal pass existed in the southern Mustang Island area until the early 1900's. Hurricanes tend to readily breach those barrier segments that are adjacent to, and on the upcurrent (longshore current) side of, tidal inlets such as North Pass on St. Joseph Island and southern Mustang Island (Price, 1952, 1956).

Padre Island (Corpus Christi and Kingsville maps) is distinctively different from barrier islands of the central and upper Texas Coast. Vegetation on Padre Island is less dense, but fore-island dunes are generally well developed southward along north Padre Island almost to Mansfield Channel. Average dune elevation is about 15 feet above MSL; maximum elevations reach about 50 feet above MSL. Near Mansfield Channel, fore-island dunes are low and discontinuous; hence, along central Padre Island, storm-surge flooding is virtually unimpeded and many breach or washover channels are concentrated in the area. Northern Padre Island beaches are generally low and broad and consist of terrigenous sand. Southward, beaches become shelly, narrow, and high. The height of back beaches increases to about 7 feet above MSL, thereby providing some protection to fore-island dunes during storms.

Bay shoreline and inland areas are severely affected by storm-surge flooding, wave erosion, and fresh-water flooding from hurricanes. Severity of storm-surge flooding and destruction of man-made and natural features by waves is chiefly a function of bay size and configuration, presence or absence of cliffs, and location of hurricane landfall. Severity of fresh-water flooding is determined by local topography and storm characteristics.

Storm-surge flooding and wave damage are greatest along the shores of large, funnel-shaped bays with relatively high cliffs at the bayhead, which lie to the right of the landfall area. As onshore winds within the right side of the hurricane strike the Coastal Zone, storm-surge height increases toward the heads of bays as the surface area of the bay decreases and cliff height increases. Flooding along Matagorda Bay and Lavaca Bay shores during Hurricane *Carla*, 1961, is an example of hurricane impact within funnel-shaped Texas bays (Bay City-Freeport and Port Lavaca maps).

Bays that lie to the left of the storm track are not as severely flooded by storm surge as those lying to the right because storm tides and waves are driven toward the Gulf of Mexico on the left side of the counterclockwise wind systems. In this situation, most of the surge and wave attack is directed toward the back side of peninsulas and barrier islands.

Low-lying areas, such as marshes, delta plains, and river floodplains, are commonly flooded by storm surge. River floodplains and flat upland areas also may be extensively flooded by rainfall associated with a hurricane that moves slowly inland. Unless these areas are inhabited, little damage occurs; salt to brackish marshes are temporarily freshened. Floodplains may pond water for months.

Population Density

Storm-surge flooding, breaking waves, wind, and fresh-water flooding may cause considerable destruction in areas that are sparsely populated, but because of the low population density, this kind of natural damage does not significantly affect man. Perhaps the severity of a hurricane should, therefore, be measured in terms of its impact on man and man-made structures or developments—according to this viewpoint, the greater the population density, obviously the greater the severity of the storm.

Hurricane *Celia* was a small hurricane with high-velocity winds, which damaged or destroyed many man-made structures in the populated Corpus Christi region. In monetary terms, *Celia* was a severe storm. Had *Celia* made landfall on deserted central Padre Island and moved westward over the sparsely populated eolian sandplain, there would have been very little loss of life or damage to man-made structures. In such a setting, *Celia* would not have been a severe storm.

PREDICTION OF SEVERE HURRICANE DAMAGE

The most severe storm damage can be expected when large hurricanes of the *Carla* type make landfall (1) where barrier islands or peninsulas are of low relief (fore-island dunes are poorly developed or absent), (2) where sands constituting barrier islands or peninsulas are relatively thin, (3) where elongate bays lie to the right of the hurricane track, and (4) where the landfall area is densely populated. Examples of situations (1) and (2) are Matagorda Peninsula and south Padre Island. Funnel-shaped or elongate bays that may be the sites of extreme storm-surge flooding (situation 3) are Trinity, Galveston, Lavaca, San Antonio, Corpus Christi, and Nueces Bays. Densely populated areas and areas that are currently experiencing rapid development (situation 4), which can be expected to be severely damaged by a *Carla*-type hurricane, are the south Padre Island area, the Corpus Christi area (including the smaller cities adjacent to the bays), the Port Lavaca area, the Galveston-Houston area, and the Beaumont-Port Arthur area.

The *Beulah*-type hurricane causes extensive flooding. Man-made structures (i.e., residences, farm buildings, recreational facilities) situated on floodplains and adjacent to creeks and rivers can be expected to be damaged or destroyed. A storm such as *Beulah* in 1967, or *Carmen* in 1974, does not necessarily have to make landfall along the Texas Coast to cause flooding along Texas creeks and rivers. For example, *Carmen* struck the Louisiana coastline during the first week of September in 1974. She was still influencing weather in Texas as late as the second week in September, triggering excessively heavy rainfall in the Coastal Zone between Port Lavaca and Sinton. During the early morning of 13 September 1974, up to 17 inches of rain fell on the Papalote Creek drainage, a tributary to Aransas River. Flooding of Papalote Creek from this heavy rainfall was greater than the flooding experienced during the earlier Hurricane *Beulah* rains.

MITIGATION OF HURRICANE IMPACT

Hurricanes cost the people of Texas millions of dollars (table 6). Several methods have been employed to reduce the destructive potential of hurricanes. Mitigation of the hurricane hazard is in part accomplished by (1) reliable forecasting and prediction, (2) formulating evacuation procedures, (3) strengthening natural defenses such as fore-island dunes, and (4) erecting rigid structures to withstand wave attack or to retard waves and prevent storm-surge flooding. Another possible method of reducing the destructive potential of a storm lies in altering the storm itself. Finally, the most certain means of reducing storm damage is avoidance. Need for mitigation throughout the Atlantic and Gulf coasts becomes progressively more urgent since there was a 40-percent increase in beach residents between 1960 and 1970 (Frank, 1974). Although numerous problems arise from such rapid growth in the Coastal Zone, perhaps the most critical problem is the lack of hurricane experience of many of the new coastal residents.

Forecasting and prediction are now very sophisticated. Hurricanes are carefully monitored by electronic methods, by air surveillance, and by weather satellite. Residents in the vicinity of predicted landfall generally have sufficient time to evacuate the area. On the other hand, the time may be approaching when it will be impossible to entirely evacuate some coastal areas, e.g., barrier islands. A mass exodus of hundreds of thousands of people by automobile across congested causeways may not be physically possible. Two alternatives may be considered in order to reduce the number of people that would be required to flee the islands. First, with better forecasting, it may become possible to determine with even greater accuracy the "direct hit" and "fringe" areas. Evacuation of residents in the direct hit areas would be required; those in fringe areas would remain. A second alternative to evacuation would be the utilization of specially structured high rises (hotels, motels, condominiums, and apartments) as vertical refuges (Frank, 1974).

Fore-island dunes if present form the first line of natural defense against storm surge and breaking waves. The ability of dunes to withstand hurricane attack is dependent upon the density of stabilizing vegetation cover. Many dunes have been weakened or destroyed through devegetation. This occurs naturally during droughts and as a result of man's activities. Attempts have been made to strengthen dunes through artificial stabilization by increasing the vegetation density. Most notable of these ventures has been on the barrier islands of North Carolina (Dolan and Godfrey, 1973; Dolan and Odum, 1973). Artificial dune stabilization in North Carolina, however, has aggravated shoreline erosion.

Table 6. Losses from recent hurricanes. (A) Hurricane *Carla*, (B) Hurricane *Beulah*, (C) Hurricane *Celia*. Values in thousands of dollars. Data from U. S. Army Corps of Engineers (1962, 1968, 1971a). Note that data do not necessarily agree with that provided by National Oceanic and Atmospheric Administration (1900-1974).

A. HURRICANE CARLA

Type of loss	Tidal flooding	Wind and Rain	Total
Agriculture	19,544	41,314	60,858
Residential	105,779	66,441	172,220
Commercial buildings and contents	39,148	25,658	64,806
Industrial plants	11,683	3,349	15,032
Transportation	9,207	3,141	12,348
Utility	1,198	8,787	9,985
Miscellaneous	13,636	6,801	20,437
Services	–	–	52,604
Total	200,195	155,491	408,290

Lives lost: 32 persons

B. HURRICANE BEULAH

Type of loss	Tidal flooding	Wind and wind-driven rain	Stream flooding and ponding	Total
Agriculture	0	6,835	31,019	37,854
Commercial	2,241	1,192	6,370	9,803
Residential	615	21,457	25,463	47,535
Services	2,097	12,781	35,474	50,352
Total	4,953	42,265	98,326	145,544

Lives lost: 15 persons in Texas

C. HURRICANE CELIA

Type of loss	Wind damages	Tidal flooding	Total
Agriculture	19.220	13	19,233
Residential	199,652	3,523	203,175
Commercial	44,375	917	45,292
Industrial	75,980	8,705	84,685
Public	33,633	150	33,783
Transportation	540	1,186	1,726
Utilities	21,922	187	22,109
Marine	3,100	7,029	10,129
Automobiles	18,944	620	19,564
Services	22,372	5,243	27,615
Total	439,738	27,573	467,311

Lives lost: 13 persons

Estimated losses from hurricanes since 1900: $1,271,983,000

The Galveston seawall is an example of an engineering approach to retard hurricane damage, but as a result of stabilizing the shoreline, the beach has been lost. The seawall was erected specifically to protect the city against overflows from the sea (Davis, 1961). Sand, excavated from western Galveston Island, was used to fill part of the low area behind the seawall. Bulkheads and revetments are also commonly used to protect some bay shores from hurricane wave attack. Other proposed methods to alleviate potential storm surge and wave damage to bay-shore property include the use of breakwaters constructed within the bays specifically to reduce wave action, and the construction of a system of locks which, in the event of a hurricane, could close off the tidal and navigation channels.

Two other means of lessening damage potential are to avoid those areas that are prone to storm-surge and fresh-water flooding and to enact appropriate building codes; areas that have been flooded by storm surge and fresh water are shown on Natural Hazards Maps. Buildings can be constructed to withstand the high-velocity winds and sudden pressure changes associated with hurricanes. Elevation of buildings by utilizing pilings can eliminate most of the damage from storm-surge flooding, but will not eliminate damage or destruction from breaking waves.

Attempts have been made to alter the hurricane itself, and research is being conducted to determine the feasibility of altering tropical storms (Dunn and Miller, 1964; Simpson, 1966). The object of hurricane modification is to decrease the steep pressure profile (hence decrease the wind velocity) and to convert the hurricane to a tropical storm. Profiles through hurricanes and tropical storms (fig. 11) show that wind velocity and pressure gradient are greatest near the eye of a hurricane. The tropical storm, which has no eye, has a much lower wind velocity than hurricanes. At present, cloud seeding appears to be a promising method to reduce wind speed and eliminate the eye. The seeding method may never lead directly to useful modification, however, because hurricanes are so large and their energy is so enormous (Simpson, 1966). A hurricane with moderate strength releases as much condensation heat energy in a day as the nuclear fusion energy of four hundred 29-megaton hydrogen bombs. Significant modification of hurricanes may be impossible. It also may prove to be undesirable to destroy a hurricane or to alter its course, since these storms supply a quarter to a third of the rainfall in critical areas of the world.

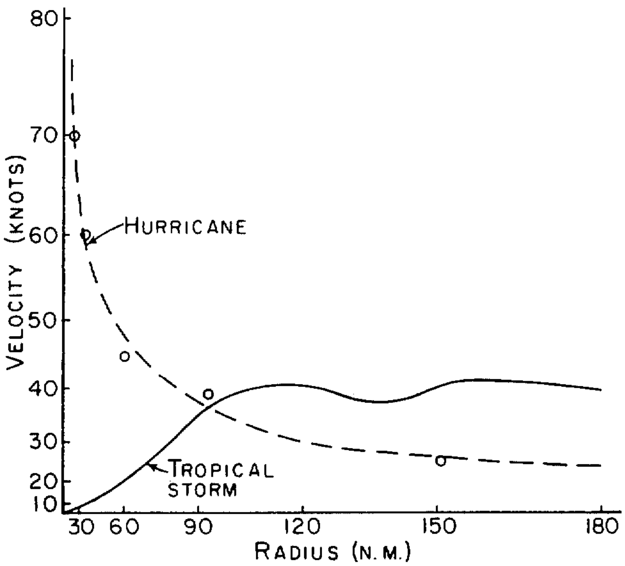


Figure 11. Velocity profiles characteristic of hurricanes and tropical storms. After Simpson (1966).

● FLOODING ●

GENERAL STATEMENT

Two principal types of flood hazards exist in the Texas Coastal Zone: storm-surge tidal flooding and fresh-water flooding. During the passage of hurricanes and tropical storms, storm-surge tides may flood low-lying coastal areas up to elevations above 20 feet (fig. 7). Fresh-water flooding, on the other hand, results from hurricane-aftermath rainfall, as well as from severe thunderstorms and frontal-related storms. Fresh-water flooding may occur as stream flooding of floodplains or as rainfall flooding of broad areas of the coastal plain. On the flat coastal plain, the runoff is ponded in natural depressions or dammed behind highways, railroads, and other man-made structures.

Shoreline erosion and land subsidence, both natural factors that can be accelerated by human impact, are increasing the hazard of storm-surge and fresh-water flooding in the Coastal Zone. As shorelines retreat, or as lands subside, greater areas of the Coastal Zone are exposed to storm-surge tides. Similarly, land subsidence, whether due to natural compaction and subsidence or to ground-water withdrawal, produces broad irregular depressions that can pond substantial volumes of rainfall on the impermeable muddy substrates of much of the lower coastal plain. Ship channels, irrigation ditches, and extensive dikes, related both to agriculture and industrial/commercial development, may also serve to aggravate the impact of the storm-surge tide and to impede rainfall runoff.

Those areas actually flooded by the storm-surge tides that accompanied Hurricanes *Carla* and/or *Beulah* (3,164 square miles) are shown on the Natural Hazards Maps. Likewise, areas flooded by Hurricane *Beulah* aftermath rainfall (2,187 square miles) define the extent of fresh-water flooding (stream flooding, ponding, and damming) in the Texas Coastal Zone between Bay City and Brownsville. Data on Hurricanes *Carla* and *Beulah* were obtained from the U. S. Army Corps of Engineers (1962, 1968) and are based on aerial photographs, drift-line observations, and a variety of recording gages. The reader is referred to the above reports, as well as to a report on Hurricane *Celia* (U. S. Army Corps of Engineers, 1971a) and a report on hurricane-surge frequency estimated for the Texas Coastal Zone (Bodine, 1969). Maps and text which were distributed as part of the Texas Hurricane Awareness Program by the Texas Coastal and Marine Council (1974) also provide information on flooding.

In the northeastern part of the Coastal Zone, where adequate hurricane-aftermath flood data are generally unavailable, areas of possible stream flooding (2,073 square miles) shown on the Natural Hazards Maps are based upon the distribution of floodplain sediments and upon the geomorphic character of the stream systems. Areas that will be flooded by ponding of excessive rainfall were not delineated for the northeastern part of the Texas Coastal Zone because the necessary mapping of subtle topographic variations is beyond the resolution of regionally available topographic maps. In addition, the degree of ponding is also related to the efficiency of highway and railroad drainage systems, which may be blocked by driftwood and other debris.

The flood-prone areas shown on the Natural Hazards Maps are, therefore, based principally upon historical or geologic evidence and not upon theoretical prediction and extrapolation methods.

FLOODING PROCESSES

Hurricanes and Tropical Storms

As previously described, the most destructive aspect of hurricanes that have struck the Texas Coast (table 4) is the impact of the storm-tidal surge; widespread forerunner tides of lesser magnitude may precede the storm-surge tides. Storm surge, which is generated within the storm by the low barometric pressure and the intense, counterclockwise winds, strikes the coast as the storm makes landfall and spreads across the low coastal plain with lethal results. Most property damage and, more critically, most deaths result from the surge of ocean water across exposed, low-lying barrier islands and mainland shorelines (table 6). Nine out of ten deaths as a result of hurricanes are caused by drownings (Texas Coastal and Marine Council, 1974). As the hurricane moves ashore, floating debris propelled by the storm surge adds to the damage inflicted by the rising water and pounding waves. The greatest property losses result both from flooding and from the battering effect of water-carried debris. The devastation imposed upon Mississippi in 1969 by Hurricane *Camille* was caused principally by a storm surge of nearly 25 feet above MSL. Most seawalls and hurricane protection dikes along the Texas Coast are less than 20 feet above sea level.

Storm-Surge Tides

A general model that illustrates the nature of storm-surge tidal flooding along the Texas coastline during approach and passage of a hurricane has been previously described (fig. 7). The elevation of the storm-surge tide generated by a hurricane is generally less on the Gulf shoreline (barrier islands, peninsulas, headlands) than along the shorelines of constricted bays and estuaries where storm-tidal surge may be significantly elevated. A storm surge greater than 10 feet above MSL, therefore, may occur within constricted bays because of superelevation of the tide on the gently sloping bottoms and on the adjacent coastal plain (fig. 9). The frequency of storm-tidal surge greater than 10 feet is consistently and substantially greater for bays than for open Gulf beaches (fig. 12).

Rainfall Flooding

Rains may precede the landfall of a hurricane, but as the storm center moves inland, heavy rainfall, often accompanied by tornadoes, generally strikes the coastal plain (fig. 7). If the hurricane moves directly inland, the period of heavy rainfall may be limited to three or four hours. If the storm moves parallel to the coastline or repeatedly changes its forward direction, excessive rains may continue for many hours or even several days. For example, in 1967 Hurricane *Beulah* remained in the South Texas area for almost three days; up to 32 inches of rain fell in the region during the five or six days following landfall (fig. 8). Stream flooding and ponding inundated 1.4 million acres of land while only 630,000 acres were flooded by storm-surge tides (U. S. Army Corps of Engineers, 1968).

Hurricane-aftermath rainfall is generally so excessive that coastal streams inundate floodplains. Floodwaters are discharged into the various Texas bays, which are already experiencing high tides. As a result, combined storm-surge tides and overbank stream flooding may devastate vast areas of the flat, lower coastal plains. As the hurricane moves inland, rainfall runoff continues to flood drainage systems; streams may discharge floodwaters into bays for many days following storm passage.

Ponding of rainfall on the coastal plain may inundate more area than stream flooding. Most of the lower 50 miles of the coastal plain is underlain by flat-lying, poorly drained, moderately to highly impermeable sediments (refer to "Environmental Geologic Atlas of the Texas Coastal Zone," Fisher and others, 1972, 1973; also Fisher, 1973); rainfall runoff is high because of this relatively impervious substrate.

Although lives may be lost in hurricane-aftermath flooding, more commonly the principal loss is to property such as bridges, highways, and homes. Thousands of persons may be left temporarily homeless by the stream flooding and ponding; transportation systems may be destroyed or blocked. Flooding also damages water and sewerage facilities, leading to the threat of epidemic diseases.

Frontal-Related Storms

Storms associated with more normal meteorologic circulation also produce flood hazards in the Coastal Zone. Although thunderstorms are generated during the summer months in the coastal region by convection, most severe weather, excluding hurricanes and tropical storms, is related to frontal systems that move eastward and southeastward across the North American continent. In the winter, polar fronts may move rapidly into the coastal area suddenly bringing low temperatures, rain, and strong northerly winds. These storms may last for two or three days, during which time some locally heavy rainfall can occur. The northerly winds may generate flood tides that inundate wind-tidal flats and other low areas, especially along the southern margins of the bays and the back sides of barrier islands. Wind-tidal flooding is slow, and it does not present a serious hazard.

During spring and fall, when polar fronts diminish in strength, the cooler air mass of the frontal system is unable to maintain its momentum against warmer Gulf air; stationary fronts (sometimes called warm fronts) result. These broad fronts, which lift warm Gulf air aloft, may remain in the coastal region for many days while generating widely distributed rainfall. Serious flooding of coastal streams may occur but rarely to the degree experienced during hurricanes and tropical storms.

FLOOD-PRONE AREAS

Storm-Surge Tidal Flooding

Between 1900 and 1972, 27 hurricanes (winds greater than 74 mph) and many less severe tropical storms (winds greater than 39 mph and less than 74 mph) struck the Texas Coast (table 4), generally in August or September (fig. 3). This constitutes a rate of one hurricane every 2.5 years. Very few areas of the Texas Coast have escaped hurricane impact during this century. Each hurricane is a rather unique storm in terms of the nature and degree of winds, storm surge, and aftermath rainfall. Every bay, barrier island, peninsula, and headland exhibits some unique physical variations which can serve to modify the impact of storm-surge tides.

Two recent well-documented hurricanes (*Carla*, 1961 and *Beulah*, 1967) have been used in this atlas to define known limits of storm-surge flooding and aftermath-rainfall flooding (table 5). Flood-surge elevations and area of flooding are based on studies by the U. S. Army Corps of Engineers (1962, 1968); flood elevations are based on drift line and various gage measurements. Although *Carla* and *Beulah* flooded 3,164 square miles, they probably do not represent ultimate hurricanes. One must assume, nevertheless, that storms such as *Carla* or *Beulah* may eventually strike other parts of the coast. For instance, should a *Carla*-type storm directly strike the Galveston area (such as the 1900 storm, table 4), the area of tidal flooding could be much greater than the actual flooding that occurred when *Carla* struck Port O'Connor. With storm flood tides of 15 feet above MSL possible on the Gulf beaches and with more than 20 feet of storm tide possible within restricted bays (fig. 12), the potential flood-prone area of the Texas Coast may be significantly greater than the net area reported for *Carla* and *Beulah* flooding.

A total of 5,787 square miles of Texas coastal plain lies below an elevation of 20 feet above MSL (table 1). Much of this land below an elevation of 20 feet may be flooded locally when maximum storm-surge conditions are focused on the specific section of the Texas shoreline.

In the *Beaumont-Port Arthur map area*, *Carla* floodwaters moved inland from the Gulf beaches for 15 to 20 miles and reached up the Neches River valley to the vicinity of Beaumont. Tidal levels ranged from 6.8 feet above MSL at Orangefield to 10.5 feet above MSL northwest of High Island. Flood levels reached 8.5 feet above MSL at the mouth of the Neches River, 7.9 feet near Port Neches, 5.0 feet near Port Acres, 7.6 feet at Port Arthur, 9.4 feet along the northern shore of Sabine Pass, 8.6 feet near Big Hill, and 8.9 feet at High Island.

A total of 583 square miles of coastal lands in the Beaumont-Port Arthur map area were flooded by Hurricane *Carla*. If the center of a *Carla*-level storm struck the Sabine Lake area, tidal flooding might inundate areas up to elevations of 15 to 20 feet, hence covering 20 to 30 percent more land than indicated on the Natural Hazards Map. Although only two hurricane washover channels have been recognized near High Island, Hurricane *Carla* floodwaters apparently crossed the low-lying shoreline at many points to flood the broad marshlands along the Intracoastal Canal.

In the *Galveston-Houston map area*, *Carla* flooding extended inland for 15 miles in the Angleton area, covered most of Galveston Island and Bolivar Peninsula, most of Smith Point area, and extended up the Trinity and San Jacinto river valleys. Flooding along the western side of Galveston Bay extended up Dickinson Bayou and Clear Creek to Interstate 45. On the Gulf beaches, maximum tidal levels of 9.6 and 12.1 feet above MSL were recorded on Bolivar Peninsula and central Galveston Island, respectively. Tide levels reached 14.0 feet above MSL at Wallisville, 13.4 feet at Anahuac, 9.8 feet at Smith Point, 14.1 feet at Baytown, 15.0 feet at Morgan Point, 14.2 feet at the mouth of Clear Creek, 12.7 feet at Dickinson, 11.0 feet at Texas City, and 14.7 feet at Chocolate Bayou.

Hurricane *Carla* tidal waters flooded 694 square miles of the Galveston-Houston map area. If tidal flooding were to approach 15 to 20 feet in the Galveston Bay vicinity as a result of the direct impact of the center of a *Carla*-level storm, perhaps 10 to 20 percent more land area would be flooded than indicated on the Natural Hazards Map. Seven potential washover channels occur on Galveston and Follets Islands; other channels may develop during severe hurricanes.

Continued land subsidence centered in the Baytown region is yearly subjecting greater areas to potential tidal flooding. If the flood levels that occurred in Galveston Bay during Hurricane *Carla*, in 1961, were to strike Galveston Bay today, it is estimated that approximately 70 additional square miles would be subjected to flooding because of land subsidence (Texas Coastal and Marine Council, 1974).

In the *Bay City-Freeport map area*, tidal flooding by Hurricane *Carla* extended inland approximately 10 miles from the Gulf beach. Most of Matagorda Peninsula and the Colorado River delta were inundated and flood tides moved from 3 to 8 miles inland from the shoreline of east and west Matagorda Bay. Flood-tidal levels were measured at 10.9 feet above MSL at the mouth of the Brazos River and 5.2 feet above MSL at the Freeport channel; other levels include 13.8 feet above MSL at a site on the Brazos River about 7 miles inland, 11.0 feet near the mouth of the San Bernard River, 13.7 feet about 10 miles inland along the San Bernard River, 14.1 feet on Lake Austin, 13.7 feet along the Intracoastal Canal on the north side of East Matagorda Bay, 15.3 feet near the town of Matagorda, and 15.4 feet at Palacios.

Hurricane *Carla* tidal surge flooded 564 square miles of coastal lands in the Bay City-Freeport map area. The Bay City-Freeport map area was situated to the right of *Carla's* center when the hurricane made landfall. This location, relative to the hurricane's eye, received some of the most intense winds and storm tides experienced along the entire coast. If tidal-flood levels were to approach 15 to 20 feet in the area, perhaps 10 percent more land area would be flooded than indicated on the Natural Hazards Map. Numerous hurricane washover sites occur along Matagorda Peninsula.

The eye of Hurricane *Carla* crossed the Texas coastline at Pass Cavallo, located in the *Port Lavaca map area*. Flood tides were highly elevated in Carancahua Bay, Keller Bay, and Lavaca Bay. Tidal waters moved from 10 to 18 miles up Garcitas Creek and the Lavaca River, respectively. Most of the land area between Seadrift and Port Lavaca was flooded; very little of Matagorda Island remained emergent. Extensive flooding occurred in the Green Lake-Guadalupe delta area, along Blackjack Peninsula, and in the vicinity of St. Charles Bay.

Measured *Carla* tidal-flood levels in the Port Lavaca map area include 18.4 feet above MSL on the west side of Carancahua Bay, 20.1 feet at the State Highway 35 bridge over the upper part of Carancahua Bay, 16.3 feet in Keller Bay, 17.3 feet at Point Comfort, 22.0 feet at Port Lavaca, 15.4 feet near Port O'Connor, 10.3 feet at the ship channel on Matagorda Peninsula, 12.3 feet along the west side of Pass Cavallo, 12.1 feet at Matagorda Island Air Force Base, 11.2 feet at Seadrift, 10.3 feet on the west side of San Antonio Bay, and 7.3 feet at the State Highway 35 bridge over Copano Bay. Hurricane *Carla* tidal surge flooded 495 square miles in the Port Lavaca map area. Tidal-flood levels generally coincided with the 20-foot-elevation contour line along and to the right of *Carla's* landfall. Had *Carla* made landfall at St. Joseph Island, perhaps an additional 5 to 10 percent of the western part of the Port Lavaca area would have been inundated by tidal floodwaters. Two hurricane washover channels have been recognized near the western end of Matagorda Peninsula; Vinson Slough on St. Joseph Island is a major washover channel.

In the *Corpus Christi map area*, land inundated by tidal flooding by Hurricane *Carla* in 1961 slightly exceeded the area flooded by Hurricane *Beulah*, which made landfall near the Rio Grande in 1967. *Carla's* tidal surge flooded most of southern St. Joseph Island, Mustang Island, and northern Padre Island, except for elevated areas comprising fore-island dunes and stabilized blowout dunes. Tidal flooding extended for 10 miles up the Mission, Aransas, and Nueces river valleys. Low-lying areas surrounding Port Bay were similarly inundated. Minor tidal flooding occurred along the landward sides of Corpus Christi Bay and northern Laguna Madre. Measured *Carla* tidal-flood levels include 7.3 feet above MSL at the mouth of the Aransas River, 7.9 feet on the east side of Port Bay, 7.5 feet near Key Allegro, 9.3 feet at Port Aransas, and 5.9 feet at the southeast end of Live Oak Peninsula near Ingleside. Measured *Beulah* tidal-flood elevations in the Corpus Christi map area include 8.0 feet above MSL on northern Mustang beach, 7.3 feet at Portland, 7.3 feet near the bay bridge at Corpus Christi, 8.2 feet at the Corpus Christi Naval Air Station, 6.8 feet at the Flour Bluff bridge, and 8.8 feet in upper Oso Bay.

The elevation of *Carla's* tidal surge significantly diminished southwestward across the Corpus Christi map area; this region was located on the left or low-intensity side of *Carla's* storm center (fig. 9). Hurricane *Carla's* tidal flooding inundated 203 square miles in the Corpus Christi map area; Hurricane *Beulah* flooded only slightly less area. If the center of a *Carla*-level storm made landfall at Port Aransas, tidal levels might reach 15 to 20 feet above MSL and an additional 10 to 15 percent of the land area would be flooded by the surge, particularly in the Port Bay and Laguna Larga-Oso Bay areas. Broad hurricane washover channels occur at the southeastern end of St. Joseph

Island and in the Packery-Newport-Corpus Christi channel area on southern Mustang and northern Padre Islands.

Storm-surge tides generated by Hurricane *Beulah* in the *Kingsville map area* far exceeded *Carla's* tidal flooding in the area. Hurricane *Beulah* storm tides inundated much of Padre Island, all tidal flats and low-lying areas along the landward side of Laguna Madre, large areas adjacent to Baffin Bay, and the lower reaches of Olmos Creek, San Fernando Creek, and Petronilla Creek. Hurricane *Beulah* tidal flooding inundated 288 square miles in the Kingsville map area. Measured *Beulah* flood-tide elevations include 8.7 feet above MSL at Malaquite Beach (Padre Island National Seashore), 5.6 feet at Penascal Point at the mouth of Baffin Bay, 8.8 feet near Loyola Beach, and 10.9 feet along the lower reaches of San Fernando Creek.

If the center of a *Beulah*- or *Carla*-level storm were to make landfall along north-central Padre Island, 10 to 15 percent more land would probably be inundated by tidal flooding, especially in the Baffin Bay region, on Padre Island, and within low areas associated with the extensive sand dune fields. Much of Padre Island near the land-cut area was breached by hurricane washover channels.

In the *Brownsville-Harlingen map area*, Hurricane *Beulah* tidal flooding inundated most of southern Padre Island and all of the extensive tidal flats, particularly in the Arroyo Colorado area and in the vicinity of the Brownsville ship channel. Hurricane *Beulah* did not strike the south Texas Coast head-on, but moved into the region from Mexico, almost parallel to the coastline. For this reason, the Brownsville region may have experienced lower storm tides than it would if the hurricane had moved directly westward out of the Gulf of Mexico.

Measured *Beulah* tidal elevations include 6.9 feet above MSL at Port Mansfield, 3.5 feet on the Gulf beach south of Mansfield jetty, 5.3 feet along the Intracoastal Canal at the mouth of Arroyo Colorado, 3.9 to 7.4 feet on southernmost Padre Island, 7.5 feet on the Gulf beach at Boca Chica, 6.3 feet near Port Isabel, and 8.5 feet along State Highway 48, halfway between Boca Chica and Brownsville. Sugg and Pelissia (1968) reported a high-water mark of 12 feet above MSL in a house at south Port Isabel. Hurricane *Beulah* tidal surge flooded 336 square miles in the Brownsville-Harlingen map area; much of this flooded area consists of low tidal flats. If the center of a *Beulah*- or *Carla*-level storm were to strike the south Texas Coast while moving westward or southwestward, a significantly greater land area than indicated on the Natural Hazards Maps might be flooded.

Stream Flooding and Ponding

On the Natural Hazards Maps, flood-prone areas resulting from rainfall associated with tropical storms, hurricanes, and frontal systems are based on two sources: (1) data on Hurricane *Beulah* flooding (U. S. Army Corps of Engineers, 1968) served as a guide to flood-prone areas in South Texas between the Rio Grande and the Lavaca/Navidad River system; and (2) aerial photographs, topographic maps, and field observations were used to delineate flood-prone areas (based on geologic/geomorphic evidence) between the Lavaca/Navidad River system and the Sabine River where regional rainfall flood data are unavailable. The use of *Beulah* stream flooding and ponding data provides an actual historical example of flooded areas. It should be realized, however, that the fresh-water flood area shown on the Natural Hazards Maps is probably a conservative estimate below the maximum flood levels which can occur in the region. Northeast of the Lavaca/Navidad River basin, flood-prone areas are underlain by floodplain sediments, which are geologic evidence of flooding.

In the *south coastal areas*, Hurricane *Beulah* delivered approximately 30 inches of rainfall in less than one week. It is one of the best documented flood events in the region. Although *Beulah*-related rainfall was general in the region, certain areas received anomalous quantities of precipitation. For this reason, one must recognize that the fresh-water flood limits on the Natural Hazards Maps are not based upon uniform rainfall within each stream system.

Every stream between the Rio Grande and the Lavaca/Navidad Rivers experienced flooding; the general limits of flooding are shown on the Natural Hazards Maps. Flooding inundated 2,187 square miles (table 1). Extensive ponding occurred between Baffin Bay and the North Floodway/Arroyo Colorado area, where stream drainage is essentially nonexistent within the broad fields of sand dunes. Impervious substrates, which occur locally beneath the dunes, coupled with the hummocky sand ridges and blowout depressions, ponded the rainfall and inhibited its runoff to the Gulf of Mexico. Earthen embankments along State Highway 77 and the Missouri Pacific Railroad locally retarded runoff. Ponded water remained for months before evaporation and slow percolation combined to lower water levels.

In the *northeast coastal area* between the Lavaca/Navidad Rivers and the Sabine River, *Beulah* rainfall was insufficient to produce stream flooding and ponding. Because of the absence of regional historic rainfall data for the upper region of the Texas Coastal Zone, flood-prone areas on the Natural Hazards Maps are based on geologic and geomorphic evidence. On the Natural Hazards Maps, these areas, which cover 2,073 square miles (table 1), are called "potential areas of fresh-water flooding by hurricane rainfall." The areas are underlain by floodplain sediments, which verify their flood potential. This flood category is comprised chiefly of river or stream valleys and adjacent depressed, poorly drained areas that occasionally may be flooded by overbank discharge of the stream, as well as by intensive hurricane rainfall. Such flood-prone areas can be delineated with reasonable accuracy, but they do *not* represent flooding by a single, observed flood event similar to that caused by *Beulah* rainfall.

Delineation of potential areas of ponding are not included for the northeastern part of the Coastal Zone. Ponding results from a complex interplay of subtle topographic depressions, water-table elevations, man-made structures, and available drainage systems. For this reason, the precise limits of ponding can best be determined by actual experience. Ponding rarely leaves a distinctive geologic deposit that can be used to determine its limits.

Predicting Flood-Prone Areas

Meteorologists and engineers have correctly placed a high priority on learning to predict the level of tidal surge caused by hurricanes. When enough is known about tidal levels, wind direction and intensity, atmospheric pressure, and other factors, it may be possible to construct reasonably accurate hurricane prediction models. Hurricanes strike Texas an average of once every 2.5 years. Meager quantitative data are available on most of these storms, especially data at many sites along the Gulf beaches and within the bays. For this reason, insufficient data exist at this time to develop a truly accurate and statistically valid model (Bodine, 1969). A dense network of tidal gages and other recorders are needed throughout the region. Even if such a data system were now available, it would take many years to sample a sufficient number of hurricanes to generate highly reliable prediction models.

By using a combination of observational information and logic, some progress has been made in predicting the level of storm-tidal surge. One such method (Bodine, 1969) is based on a hypothetical hurricane with a central pressure index frequency probability of once in 100 years (fig. 12). This hypothetical hurricane is the Standard Project Hurricane of the U. S. Army Corps of Engineers, if it generates maximum surge at a specific, selected location.

Because the Gulf beaches are relatively straight and offshore bathymetry generally uniform, estimates of surge elevations are probably significantly more accurate on the Gulf shoreline than within the highly complex and variable bays. The variety of bathymetry, shoreline configuration, and other factors make accurate prediction of surge within bays much more difficult. Estimates of the frequency of surge heights on the Gulf shore at Freeport and within Galveston Bay at Baytown are shown on figures 12A and 12B; figure 12C shows predicted Gulf beach tidal elevations along the entire Texas Gulf Coast.

Hurricane-tidal levels will be predicted with increasing accuracy, especially along the Gulf beaches. Because of the variability of the Gulf hurricane, its path, and its interaction with the highly variable configuration of Texas bays, precise prediction of maximum flood levels will take many years to perfect. In the meantime, the charting of observed flood events provides a valuable guide to flood-prone areas.

MITIGATION AND AGGRAVATION OF FLOODING

Before man settled the Texas Coastal Zone, hurricane processes, along with all coastal and marine processes, were generally in equilibrium with the natural coastal environments. Hurricanes are but one of a large number of natural phenomena that probably have operated for tens of thousands of years in the Texas coastal region. Before man arrived, the storms expended much of their great energy in the coastal system and brought about, in a natural way, certain physical and biologic changes. The slow evolution of the Texas Gulf Coastal Zone has been affected by the tropical cyclone.

Tropical storms and hurricanes have effected certain changes in the region; barrier islands were modified and, perhaps, even their origin was, in part, controlled by such storms. Bays were flushed and supplied with marine nutrients; sediment was eroded and redistributed. When man became part of the coastal system, however, hurricanes became disastrous because man does not necessarily live in equilibrium with the natural environment. Hurricanes have become severe problems today because they strike man's habitation and development. It is important during this period of growing population and development in the coastal region that man strive to live in harmony with the hurricane, while at the same time developing safeguards to prevent loss of life and to minimize loss of property.

Many natural features of the coastal area tend to mitigate the impact of hurricane flooding on man-made structures and developments. In addition, man has attempted to alleviate the danger and destruction caused by the hurricane floods in a variety of ways, most of which involve protective structures. It is probable that man can significantly improve his safety and can reduce storm damage by careful development

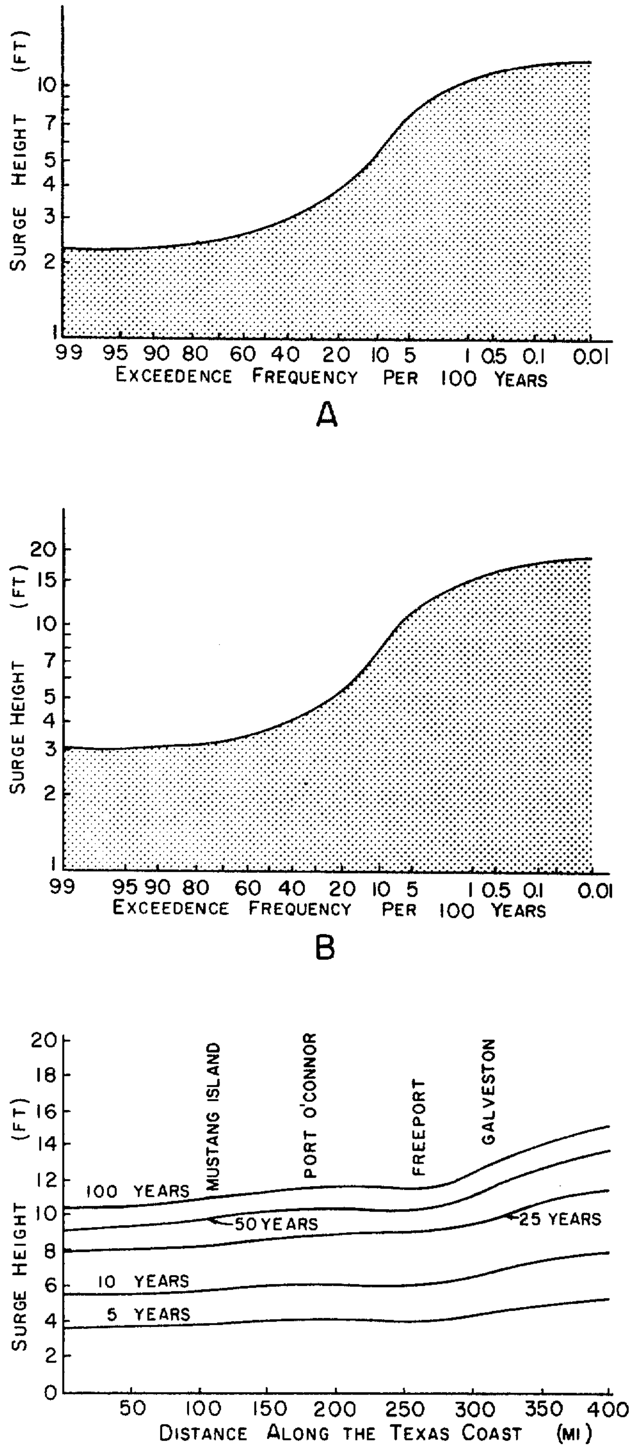


Figure 12. Estimation of storm-surge height and frequency, Texas Gulf Coast. Based on mathematical methods. After Bodine (1969). (A) Gulf beaches at Freeport, (B) Bay shoreline at Baytown, Galveston Bay, (C) Predicted tidal elevations (in terms of exceedence frequency) along entire open Gulf Coast.

of building codes and construction methods. In some areas, nevertheless, it may prove to be thoroughly impractical for man to try to control the impact of storm surge. In these flood-prone areas, it may be more profitable to avoid a potential disaster by utilizing the areas for more compatible uses than habitation.

Natural Flood Protection

In the coastal region, the first natural defense against hurricane surge is the barrier island, which constitutes a barrier to waves generated on the inner shelf. The fore-island dune ridge is an important element which allows the barrier island to block effectively some of the storm-surge energy. The barrier islands, however, are effective in absorbing some of the storm's energy only if they are well stabilized by vegetation. Along the shoreline of the bays, extensive marshes and shallow grassflats provide a buffer or baffle which dampens some of the erosive power and wave energy generated by tropical storms. Marshes, like vegetated barrier islands, are resistant to storm erosion. Elongate oyster reefs, which grow upward from the bay bottom to within 1 to 3 feet of the water surface, provide a natural baffling system that aids in reducing tidal surge and that reduces the effective fetch of waves within the bays.

Land Use and Coastal Flooding

A number of man's activities may aggravate the destructive power of the storm-tidal surge and fresh-water flooding. Any activity that destroys stabilizing vegetation will weaken and subject a barrier island or a bay shoreline to increased storm-tidal erosion. Additional hurricane washover channels may develop if fore-island dunes are destroyed. Navigation passes constructed through barrier islands provide additional routes by which storm-surge tides may enter the restricted bays. Construction of channels, dikes, or any other modification which can serve to divert or focus storm tides may lead to acceleration of natural shoreline erosion. Land subsidence resulting from use of ground water exposes greater areas of the coast to the impact of tidal surge and flooding. Modification of stream courses to provide better drainage can also lead to accelerated erosion and, perhaps, even expose new areas to stream flooding and ponding. Structures that cross stream courses may impede the flow of floodwaters; similarly, ponding may develop because runoff is impeded by man-made structures.

Flood Prevention Structures

Under the pressure of growing population and industrialization, man has impinged upon more and more flood-prone areas; for example, homes and businesses are constructed within areas that have historically flooded. Dikes, berms, levees, seawalls, groins, and bulkheads have been constructed to protect life and property in flood-prone coastal areas.

Every reasonable effort should be made to protect life and property from the threat of hurricane flooding. Maximum use of premium coastal lands will require that more extensive flood protection structures be engineered and built. New and innovative methods of construction, along with improved building codes, should be an effective means of diminishing flood damage. It is important, nevertheless, to consider the rational limits on coastal construction aimed at flood prevention. More importantly, at some point, man must decide how far he can afford to go to eliminate flooding in low-lying coastal areas. Areas that are repeatedly and severely flooded might best be utilized for activities that preclude extensive property damage and safety hazards.

● SHORELINE EROSION ●

GENERAL STATEMENT

Shorelines are in a state of erosion, accretion, or equilibrium, either naturally or artificially. Erosion produces a net loss in land, accretion produces a net gain in land, and equilibrium conditions produce no net change. Shoreline changes are the response of the beach to a hierarchy of natural cyclic phenomena including (from lower to higher order) tides, storms, sediment supply, and relative sea-level changes. Time periods for these cycles range from one day to several thousand years. Most beach segments undergo both erosion and accretion in response to lower order events no matter what their long-term trends may be. Furthermore, long-term trends can be unidirectional or cyclic; that is, shoreline changes may persist in one direction, either accretion or erosion, or the shoreline may undergo repetitive periods of erosion and accretion. Shoreline erosion assumes importance along the Texas Coast because of active loss of land, as well as the potential damage or destruction of piers, dwellings, highways, and other structures.

SHORELINE MONITORING PROGRAM

In 1972, the Bureau of Economic Geology initiated a program in historical monitoring for the purpose of determining, on a quantitative basis, long-term shoreline changes in the Texas Coastal Zone. The recent acceleration in Gulf-front real estate and industrial development has provided the incentive for adequate evaluation of shoreline characteristics. Of special concern has been the documentation of those shorelines undergoing erosion and accretion, as well as those that are in equilibrium.

The first effort in this shoreline monitoring program was an investigation of Matagorda Peninsula and the adjacent Matagorda Bay area, a cooperative study by the Bureau of Economic Geology and the General Land Office of Texas. In this study, basic techniques of historical monitoring were developed (McGowen and Brewton, 1975).

In 1973, the Texas Legislature appropriated funds for the Bureau of Economic Geology to conduct historical monitoring of the entire 367 miles of Texas Gulf shoreline during the 1973-1975 biennium. Results of the project will be published ultimately in the form of detailed, cartographically precise shoreline maps. Work versions of these maps (scale 1:24,000) will be on open file at the Bureau of Economic Geology until publication. In advance of the final report and maps, a series of preliminary interim reports (e.g., Morton, 1974; Morton and Pieper, 1975) is being published.

GENERAL METHODS AND PROCEDURES

Definition

Historical Shoreline Monitoring is the documentation of direction and magnitude of shoreline change through specific time periods using accurate vintage charts, maps, and aerial photographs.

Sources of Data

Basic data used to determine changes in shoreline position are near-vertical aerial photographs and mosaics and topographic charts. Accurate topographic charts dating from 1850, available through the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), were mapped by the U. S. Coast Survey using plane table procedures. Reproductions of originals are used to establish shoreline position (mean high water) prior to the early 1930's. Aerial photography supplemented and later replaced regional topographic surveys in the early 1930's; therefore, subsequent shoreline positions are mapped on individual stereographic photographs and aerial photographic mosaics representing a diversity of scales and vintages. These photographs show shoreline position based on the sediment-water interface at the time the photographs were taken.

Procedure

The key to comparison of various data needed to monitor shoreline variations is agreement in scale and adjustment of the data to the projection of the selected map base; U. S. Geological Survey 7.5-minute quadrangle topographic maps (1:24,000 or 1 inch = 2,000 feet) are used for this purpose. Topographic charts and aerial photographs are either enlarged or reduced to the precise scale of the topographic maps. Shorelines shown on topographic charts and sediment-water interface mapped directly on sequential aerial photographs are transferred from the topographic charts and aerial photographs onto the common base map mechanically with a reducing pantograph or optically with a Saltzman projector. Lines transferred to the common base map are compared directly and measurements are made to quantify any changes in position with time.

Factors Affecting Accuracy of Data

Documentation of long-term changes from available records, referred to in this report as *historical monitoring*, involves repetitive sequential mapping of shoreline position using coastal charts (topographic surveys) and aerial photographs. This is in contrast to short-term monitoring which employs beach profile measurements and/or the mapping of shoreline position on recent aerial photographs only. There are advantages and disadvantages inherent in both techniques.

Long-term historical monitoring reveals trends which provide the basis for projection of future changes, but the incorporation of coastal charts dating from the 1850's introduces some uncertainty as to the precision of the data. In contrast, short-term monitoring can be extremely precise. However, the inability to recognize and differentiate long-term trends from short-term changes is a decided disadvantage. Short-term monitoring also requires a network of stationary, permanent markers which are periodically reoccupied because they serve as a common point from which future beach profiles are made. Such a network of permanent markers and measurements has not been established along the Texas Coast and even if a network was established, it would take considerable time (20 to 30 years) before sufficient data were available for determination of long-term trends.

Because the purpose of shoreline monitoring is to document past changes in shoreline position and to provide basis for the projection of future changes, the method of long-term historical monitoring is preferred.

Original Data

Topographic surveys.—Some inherent error probably exists in the original topographic surveys conducted by the U. S. Coast Survey [U. S. Coast and Geodetic Survey, now called National Ocean Survey]. Shalowitz (1964, p. 81) states ". . . the degree of accuracy of the early surveys depends on many factors, among which are the purpose of the survey, the scale and date of the survey, the standards for survey work then in use, the relative importance of the area surveyed, and the ability and care which the individual surveyor brought to his task." Although it is neither possible nor practical to comment on all of these factors, much less attempt to quantify the error they represent, in general the accuracy of a particular survey is related to its date; recent surveys are more accurate than older surveys. Error can also be introduced by physical changes in material on which the original data appear. Distortions, such as scale changes from expansion and contraction of the base material, caused by reproduction and changes in atmospheric conditions, can be corrected by cartographic techniques. Location of mean high water is also subject to error. Shalowitz (1964, p. 175) states ". . . location of the high-water line on the early surveys is within a maximum error of 10 meters and may possibly be much more accurate than this."

Aerial photographs.—Error introduced by use of aerial photographs is related to variation in scale and resolution, and to optical aberrations.

Use of aerial photographs of various scales introduces variations in resolution with concomitant variations in mapping precision. The sediment-water interface can be mapped with greater precision on larger scale photographs, whereas the same boundary can be delineated with less precision on smaller scale photographs. Stated another way, the line delineating the sediment-water interface represents less horizontal distance on larger scale photographs than a line of equal width delineating the same boundary on smaller scale photographs. Aerial photographs of a scale less than that of the topographic base map used for compilation create an added problem of imprecision because the mapped line increases in width when a photograph is enlarged optically to match the scale of the base map. In contrast, the mapped line decreases in width when a photograph is reduced optically to match the scale of the base map. Furthermore, shorelines mechanically adjusted by pantograph methods to match the scale of the base map do not change in width. Fortunately, photographs with a scale equal to or larger than the topographic map base can generally be utilized.

Optical aberration causes the margins of photographs to be somewhat distorted and shorelines mapped on photographic margins may be a source of error in determining shoreline position. However, only the central portion of the photographs are used for mapping purposes, and distances between fixed points are adjusted to the 7.5-minute topographic base.

Meteorological conditions prior to and at the time of photography also have a bearing on the accuracy of the documented shoreline changes. For example, deviations from normal astronomical tides caused by barometric pressure, wind velocity and direction, and attendant wave activity may introduce errors, the significance of which depends on the magnitude of the measured change. Most photographic flights are executed during calm weather conditions, thus eliminating most of the effect of abnormal meteorological conditions.

Interpretation of Photographs

Another factor that may contribute to error in determining rates of shoreline change is the ability of the scientist to interpret correctly what he sees on the photographs. The most qualified aerial photograph mappers are those who have made the most observations on the ground. Some older aerial photographs may be of poor quality, especially along the shorelines. On a few photographs, both the beach and swash zone are bright white (albedo effect) and cannot be precisely differentiated; the shoreline is projected through these areas, and therefore, some error may be introduced. In general, these difficulties are resolved through an understanding of coastal processes and a thorough knowledge of factors that may affect the appearance of shorelines on photographs.

Use of mean high-water line on topographic charts and the sediment-water interface on aerial photographs to define the same boundary is inconsistent because normally the sediment-water interface falls somewhere between high and low tide. Horizontal displacement of the shoreline mapped using the sediment-water interface is almost always seaward of the mean high-water line. This displacement is dependent on the tide cycle, slope of the beach, and wind direction when the photograph was taken. The combination of factors on the Gulf shoreline which yield the greatest horizontal displacement of the sediment-water interface from mean high water are low tide conditions, low beach profile, and strong northerly winds. Field measurements indicate that along the Texas Gulf Coast, maximum horizontal displacement of a photographed shoreline from mean high-water level is approximately 125 feet under these same conditions. Because the displacement of the photographed shoreline is almost always seaward of mean high water, shoreline changes determined from comparison of mean high-water line and sediment-water interface will slightly *underestimate rates of erosion* or slightly overestimate rates of accretion.

Cartographic Procedure

Topographic charts.—The topographic charts are replete with a 1-minute-interval grid; transfer of the shoreline position from topographic charts to the base map is accomplished by construction of a 1-minute-interval grid on the 7.5-minute topographic base map and projection of the chart onto the base map. Routine adjustments are made across the map with the aid of the 1-minute-interval latitude and longitude cells. This is necessary because: (1) chart scale is larger than base map scale; (2) distortions (expansion and contraction) in the medium (paper or cloth) of the original survey and reproduced chart, previously discussed, require adjustment; and (3) paucity of culture along the shore provides limited horizontal control.

Aerial photographs.—Accuracy of aerial photograph mosaics is similar to topographic charts in that quality is related to vintage; more recent mosaics are more accurate. Photograph negative quality, optical resolution, and techniques of compiling controlled mosaics have improved with time; thus, more adjustments are necessary when working with older photographs.

Cartographic procedures may introduce minor errors associated with the transfer of shoreline position from aerial photographs and topographic charts to the base map. Cartographic procedures do not increase the accuracy of mapping; however, they tend to correct the photogrammetric errors inherent in the original materials such as distortions and optical aberrations.

Measurements and Calculated Rates

Actual measurements of linear distances on maps can be made to one-hundredth of an inch which corresponds to 20 feet on maps with a scale of 1 inch = 2,000 feet (1:24,000). This is more precise than the significance of the data warrants. However, problems do arise when rates of change are calculated because: (1) time intervals between photographic coverage are not equal; (2) erosion or accretion is assumed constant over the entire time period; and (3) multiple rates ($\frac{n^2 - n}{2}$, where n represents the number of mapped shorelines) can be obtained at any given point using various combinations of lines.

The beach area is dynamic and changes of varying magnitude occur continuously. Each photograph represents a sample in the continuum of shoreline changes and it follows that measurements of shoreline changes taken over short time intervals would more closely approximate the continuum of changes because the procedure would approach continuous monitoring. Thus, the problems listed above are interrelated, and solutions require the averaging of rates of change for discrete intervals. Numerical ranges and graphic displays are used to present the calculated rates of shoreline change.

Where possible, dates when individual photographs actually were taken are used to determine the time interval needed to calculate rates, rather than the general date printed on the mosaic. Particular attention is also paid to the month, as well as year of photography; this eliminates an apparent age difference of one year between photographs taken in December and January of the following year.

Justification of Method and Limitations

The methods used in long-term historical monitoring carry a degree of imprecision, and trends and rates of shoreline changes determined from these techniques have limitations. Rates of change are to some degree subordinate in accuracy to trends or direction of change; however, there is no doubt about the significance of the trends of shoreline change documented over more than 100 years. An important factor in evaluating shoreline changes is the total length of time represented by observational data. Observations over a short period of time may produce erroneous conclusions about the long-term change in coastal morphology. For example, it is well established that landward retreat of the shoreline during a storm is accompanied by sediment removal; the sediment is eroded, transported, and temporarily stored offshore. Shortly after storm passage, the normal beach processes again become operative and some of the sediment is returned to the beach. If the shoreline is monitored during this recovery period, data would indicate beach accretion; however, if the beach does not accrete to its prestorm position, then net effect of the storm is beach erosion. Therefore, long-term trends are superior to short-term observations. Establishment of long-term trends based on changes in shoreline position necessitates the use of older and less precise topographic surveys. The applicability of topographic surveys for these purposes is discussed by Shalowitz (1964, p. 79) who stated:

> "There is probably little doubt but that the earliest records of changes in our coastline that are on a large enough scale and in sufficient detail to justify their use for quantitative study are those made by the Coast Survey. These surveys were executed by competent and careful engineers and were practically all based on a geodetic network which minimized the possibility of large errors being introduced. They therefore represent the best evidence available of the condition of our coastline a hundred or more years ago, and the courts have repeatedly recognized their competency in this respect. . . ."

Because of the importance of documenting changes over a long time interval, topographic charts and aerial photographs have been used to study beach erosion in other areas. For example, Morgan and Larimore (1957), Harris and Jones (1964), El-Ashry and Wanless (1968), Bryant and McCann (1973), and Stapor (1973) have successfully used techniques similar to those employed herein. Previous articles describing determinations of beach changes from aerial photographs were reviewed by Stafford (1971) and Stafford and others (1973).

Simply stated, the method of using topographic charts and aerial photographs, though not absolutely precise, represents the best method available for investigating long-term trends in shoreline changes.

Limitations of the method require that emphasis be placed first on *trend* of shoreline changes with rates of change being secondary. Although rates of change from map measurements can be calculated to a precision well beyond the limits of accuracy of the procedure, they are most important as *relative* values; that is, do the data indicate that erosion is occurring at a few feet per year or at significantly higher rates. Because sequential shoreline positions are seldom exactly parallel, in some instances it is best to provide a range of values such as 10 to 15 feet per year. As long as users realize and understand the limitations of the method of historical monitoring, results of sequential shoreline mapping are significant and useful in coastal zone planning and development.

RESULTS OF HISTORICAL MONITORING PROGRAM

Gulf Shoreline Erosion

Long-term erosion during the past 74 to 132 years (table 1) has subjected 47 linear miles, or 13 percent, of the Texas Gulf shoreline to severe erosion and shoreline retreat (greater than 10 ft per year); 154 linear miles, representing 42 percent of the Texas Gulf shoreline, similarly has been affected by moderate long-term erosion and shoreline retreat (up to 10 ft per year). Long-term accretion has occurred along 35 percent of the Texas Gulf shoreline; 10 percent of the Gulf coastline has been in long-term equilibrium.

Short-term erosion during the past 7 to 23 years has subjected 153 linear miles, or 42 percent, of the Texas Gulf shoreline to severe erosion and shoreline retreat (greater than 10 ft per year); similarly 101 linear miles, representing 28 percent of the Texas Gulf shoreline, has been affected by moderate short-term erosion and shoreline retreat (up to 10 ft per year). Only 13 percent of the Texas Gulf shoreline is undergoing short-term accretion, while 17 percent is in short-term equilibrium.

The Gulf shoreline, as previously classified, is composed of deltaic headlands, peninsulas, and barrier islands. Areas undergoing shoreline erosion can be related to this physiographic classification on a regional scale. Deltaic headlands are comprised predominantly of mud with relatively low percentages of sand, a factor that contributes to high rates of severe shoreline erosion. Eroded mud is carried seaward where it is deposited and, hence, removed from the sediment supply system. Brazos Island and south Padre Island of the Rio Grande delta (Brownsville-Harlingen map) and the beach between San Luis Pass and Brown

Cedar Cut of the Brazos-Colorado delta (Port Lavaca map) are Holocene deltaic headlands. The Gulf shore from Sabine Pass to Rollover Pass (Beaumont-Port Arthur map) is developed on a relict (Pleistocene) deltaic headland overlain by Modern marsh and strand-plain sediments. Bolivar Peninsula (Galveston-Houston map) and Matagorda Peninsula (Bay City-Freeport map) are also undergoing erosion as a result of their close association with the sand-deficient deltaic headlands.

Barrier islands of the Texas Coast, which include Galveston, Matagorda, St. Joseph, Mustang, and north and central Padre Islands (Galveston-Houston, Bay City-Freeport, Port Lavaca, Corpus Christi, and Kingsville maps, respectively) are elongate bodies of fine-grained sand from 20 to 60 feet thick. Rates of shoreline erosion along barrier islands are generally lower because of the increased availability of sand. Apparently, the shoreline along central Padre Island (Kingsville map) is relatively stable because sand is supplied to this segment of the coast by longshore currents that converge in the general vicinity of 27 degrees North latitude (Lohse, 1955). Although considerable sand is removed from the beach by eolian processes along central Padre Island, sufficient sediment to replenish the losses is transported by net longshore currents flowing northward from the southern part of the coast and southwestward from the upper part of the coast.

Bay Shoreline Erosion

Of the 1,100 miles of bay and estuarine shoreline, 408 linear miles or 37 percent of the total bay-estuarine shoreline is undergoing varying rates of shoreline erosion (table 1). At present, research on precise rates of bay-shore erosion has not been completed; bay shorelines undergoing erosion have been interpreted qualitatively. Bay shoreline erosion is related principally to the dominant wind regimes of the region, but hurricanes and tropical storms may inflict bay shores with severe erosion during brief periods of landfall.

Southeasterly winds persist throughout the spring, summer, and fall months, whereas northerly winds of less duration but greater strength persist during the winter months. Wind strength and duration, fetch, depth of water, and orientation of bay shorelines are some of the important factors controlling bay shoreline erosion. In areas where fetch is measured in miles, the southwesterly winds generate waves and currents that impinge and erode shoreline segments along northwestern bay margins; examples occur in Trinity and Galveston Bays (Galveston-Houston map), Matagorda Bay (Bay City-Freeport map), San Antonio Bay (Port Lavaca map), Aransas and Corpus Christi Bays (Corpus Christi map), and Baffin Bay (Kingsville map), as well as in Laguna Madre (Brownsville-Harlingen map). Similarly, northerly winds generate waves that strike and erode southern and southwestern shoreline segments in Galveston, Matagorda, San Antonio, Corpus Christi, and Baffin Bays. Bay shoreline erosion along Matagorda, St. Joseph, and Mustang Islands and Matagorda Peninsula is also caused by waves and currents generated by northerly winds. Sand eroded from bay shorelines is deposited within the bay; some mud derived from shorelines may reach the Gulf, but much of it gradually fills the bay.

FACTORS AFFECTING SHORELINE CHANGES

Studies indicate that shoreline changes along the Texas Gulf Coast are largely the result of natural processes, although in some instances the changes may have been aggravated by human activities. Geologic processes and, more specifically, coastal processes are complex dynamic components of large-scale systems. Coastal processes are dependent upon the intricate interaction of a large number of natural variables such as wind velocity and duration, fetch, rainfall, storm frequency and intensity, tidal range and characteristics, and littoral currents. It is difficult, therefore, if not impossible, to isolate at this time all the specific factors causing shoreline changes.

Climate

Climatic changes during the 18,000 years since the end of the Pleistocene ice age have been documented by various methods. In general, air temperature was lower and precipitation was greater at the end of the Pleistocene than at the present; the warmer and drier conditions, which now prevail, affect other factors such as vegetal cover, runoff, sediment concentration, and sediment yield. Observations based on geologic maps prepared by the Bureau of Economic Geology ("Environmental Geologic Atlas of the Texas Coastal Zone") confirm that many rivers along the Texas coastal plain were larger and probably transported greater volumes of sediment thousands of years ago (early Holocene). This, in turn, affected the sediment budget of the Texas Coast by supplying additional sediment to the littoral drift system.

Severe droughts that occur periodically are a potential, though indirect, factor related to minor shoreline changes because of the adverse effect of low rainfall on vegetation. Because dunes and beach sand are stabilized by vegetation, sparse vegetation resulting from droughts offers less resistance to wave attack. Regional variations in rainfall and wind dominance along the Texas Coast also must exert some differential effect on shoreline stability.

Storm Frequency and Intensity

The frequency of tropical cyclones is dependent on cyclic fluctuations in temperature; increased frequency of hurricanes occurs during warm cycles (Dunn and Miller, 1964). Because of their frequent occurrence, devastating force, and catastrophic nature, tropical cyclones have received considerable attention in recent years. The significance of hurricanes as geologic agents was emphasized by Hayes (1967) who concluded that most of the Texas coastline experienced the passage of at least one hurricane eye during this century. The general nature of tropical storms and hurricanes, as well as their relationship to flood hazard, has been described in this report. The specific relationship between these storms and shoreline stability in Texas also is important in understanding the nature of rapid changes in shorelines.

As previously described, high-velocity winds with attendant waves and currents of destructive force scour and transport large quantities of sand during hurricane approach and landfall (fig. 7). The amount of damage suffered by the beach and adjoining areas depends on a number of factors including angle of storm approach, configuration of the shoreline, shape and slope of Gulf bottom, wind velocity, forward speed of the storm, distance from the eye, stage of astronomical tide, decrease in atmospheric pressure, and longevity of the storm. Beach profiles adjust themselves to changing conditions in an attempt to maintain a profile of equilibrium; shorelines experience their greatest short-term changes during and after storms. Storm surge and wave action commonly plane off preexisting topographic features and produce a featureless, uniformly seaward-sloping beach. Eroded dunes, wave-cut steps, and washover fans are common products of the surge; the sand removed by erosion is (1) transported and stored temporarily in an offshore bar, (2) transported in the direction of littoral drift, and/or (3) washed across the barrier island through hurricane channels. Sediment transported offshore and stored in the nearshore zone is eventually returned to the beach by bar migration under the influence of normal post-storm wave action. The processes involved in beach recovery are discussed by Hayes (1967) and McGowen and others (1970).

Foredunes are an important line of defense against wave attack and, thus, afford considerable protection against hurricane surge and washover. Dunes also serve as a reserve of sediment from which the beach can recover after a storm. Sand that is removed from the dunes and beach, transported offshore, and returned to the beach, provides the material from which small coppice mounds and eventually the large fore-island dunes rebuild. Dune removal, therefore, eliminates sediment reserve, as well as a natural defense mechanism established for beach protection.

Whether the beach returns to its prestorm position depends primarily on the amount of sand available. If net sand is lost, the beach profile will not reestablish itself at the prestorm position; thus, net shoreline erosion or retreat has occurred. The beach profile readjusts to normal prestorm conditions much more rapidly than does the vegetation line. Generally speaking, the sequence of events is as follows: (1) return of sand to beach and profile adjustment (accretion), (2) development of low sand mounds (coppice mounds) seaward of the foredunes or vegetation line, (3) merging of coppice mounds with foredunes, and (4) migration of vegetation line to prestorm position. The first step is initiated within days after passage of the storm and adjustment is normally attained within several weeks or a few months. The remaining steps require months or possibly years and, in some instances, complete recovery is never attained.

Local and Worldwide Sea-Level Conditions

Two factors of major importance relevant to land-sea relationships are sea-level changes and compactional subsidence. Shepard (1960b) discussed Holocene or post ice-age (Pleistocene) rise in sea level along the Texas Coast based on C^{14} age determinations. During historical time, relative sea-level changes are deduced by geodetic engineers who monitor mean sea level using tide observations to develop trends based on long-term measurements. This method, however, does not distinguish between sea-level rise and land-surface subsidence. A minor vertical rise in sea level relative to adjacent land in low-lying coastal areas causes a considerable horizontal, landward displacement of the shoreline.

Shepard and Moore (1960) speculated that coastwise subsidence was probably an ongoing process augmented by sediment compaction. More recent data tend to support the idea that natural land subsidence is occurring along the Texas Coast (Swanson and Thurlow, 1973).

Sediment Budget

Sediment budget refers to the amount of sediment in the coastal system and the balance among quantity of material introduced, temporarily stored, or removed from the system. Beaches are nourished and maintained by sand-size sediment contributed by major streams, updrift shoreline erosion, and onshore movement of shelf sand by wave action. Sand losses are attributed to (1) transportation offshore into deep water, (2) accretion along and against natural littoral barriers and man-made structures, (3) deposition in tidal deltas and hurricane washover fans, (4) excavation for construction purposes, and (5) eolian processes.

Sediment supplied by major streams is transported along the shore by littoral currents. The Brazos River, Colorado River, and Rio Grande are the only major Texas rivers that debouch directly into the Gulf of Mexico, but discharge data indicate that these rivers currently contribute very little sediment to the littoral drift system. The Mississippi River was a possible source of beach sediment prior to its shift to the eastern part of the delta about 400 years ago.

Van Andel and Poole (1960) and Shepard (1960a) suggested that sediments of the Texas Coast are largely of local origin. Sands derived from previously deposited sediment on the floor of the continental shelf were apparently reworked and transported shoreward by wave action during the post ice-age (Holocene) sea-level rise. McGowen and others (1972) also concluded that the primary source of sediment for Modern sand-rich barrier islands, such as Galveston, Matagorda, and St. Joseph Islands, was local Pleistocene and early Holocene sources on the adjacent inner shelf.

FACTORS AGGRAVATING EROSION

Shoreline changes induced by man are difficult to quantify because human activities promote alterations and imbalances in the sediment budget of the Coastal Zone. Furthermore, ground-water withdrawal increases land subsidence. Construction of dams, erection of seawalls, groins, and jetties, artificial stabilization of the Mississippi River, and removal of sediment for building purposes all contribute to changes in quantity and type of beach material delivered to the Texas Coast. Even such minor activities as vehicular traffic and beach scraping can contribute to the overall changes, although they are in no way controlling factors. Erection of impermeable structures and removal of sediment have an immediate, as well as a long-term effect, whereas a lag of several to many years may be required to evaluate fully the effect of other changes such as river control, dam construction, and subsurface fluid withdrawal.

Jetty construction along the Texas Coast was initiated in the late 1800's. These projects serve to alter natural processes such as inlet siltation, beach erosion, and hurricane surge. Their effect on shoreline changes is subject to debate, but it is an obvious fact that impermeable structures interrupt littoral drift, and impoundment of sand occurs at the expense of beach nourishment downdrift of the structure. It appears reasonable to expect that any sand trapped by the jetties is compensated for by removal of sand downdrift, thus increasing local erosion problems.

Factors which have contributed to the deficit in sediment budget include: (1) removal of sand from the fore-island dunes, (2) dredging of sand from the Gulf, (3) excavation of sand from barrier islands and peninsulas, (4) construction of dams on the Rio Grande and Brazos River, and (5) artificial maintenance of the current position of the Mississippi River.

LONG-TERM TRENDS IN SHORELINE POSITION

Shore erosion is not only a problem along United States coasts but also is a problem worldwide. Even though some local conditions may aggravate erosion, major factors affecting shoreline changes are sea-level variation, including compactional subsidence, and a deficit in sediment supply. A deficit in sand supply may be related to climatic changes, human activities, and the exhaustion of the shelf supply through subsequent burial of shelf sand by finer sediments to a depth below wave scour.

A logical conclusion that can be drawn from available information is that shoreline position will continue to change, and landward retreat (erosion) will be the long-term trend. The combined influence of interrupted and decreased sediment supply, relative sea-level rise, and tropical cyclones is insurmountable except in very local areas such as river mouths. There is no evidence to suggest that a long-term reversal may occur in the foreseeable future to change the present trends of shoreline change.

POTENTIAL MITIGATION OF SHORELINE EROSION

The best defense against the hazard of shoreline erosion is recognition and subsequent adjustment in land use. Other alternatives include artificial beach nourishment or artificial stabilization by dune vegetation and structures.

It should be noted, however, that dune stabilization, while appearing to be environmentally sound, can be counterproductive and may have a definite impact on beach steepness and erosion. This was demonstrated on the North Carolina coastline where vegetated dunes resisted storm wave attack so well that the normal exchange of sand between the dunes and beach was eliminated; increased beach steepness and beach erosion resulted from this effort to stabilize the dunes (Dolan and Godfrey, 1973).

The shoreline in Texas could be stabilized at enormous expense by a solid structure such as a seawall. Any beach seaward of such a structure would eventually be removed unless maintained artificially by sand nourishment (a costly and sometimes ineffective practice). The U. S. Army Corps of Engineers (1971b, p. 33) stated: "While seawalls may protect the upland, they do not hold or protect the beach which is the greatest asset of shorefront property." Moreover, construction of a single structure may trigger a chain reaction that will require additional structures and maintenance.

When development plans are being formulated, careful consideration must be given to the evidence that shoreline erosion will continue into the foreseeable future. While beach-front property may demand the highest prices, it may also carry with it the greatest risks.

● LAND-SURFACE SUBSIDENCE ●

GENERAL STATEMENT

Land-surface subsidence, primarily a consequence of ground-water pumping and withdrawal that began in the Texas Coastal Zone in the early part of this century, affects to varying degrees a substantial part of the lower Texas coastal plain. Most serious subsidence is in the Greater Houston area, where some localities show recorded subsidence up to 8.5 feet (Galveston-Houston map). Significantly, both the rate of land subsidence, in terms of lost land elevation, and the area of impact are progressively increasing and have increased dramatically in the past two decades (fig. 13).

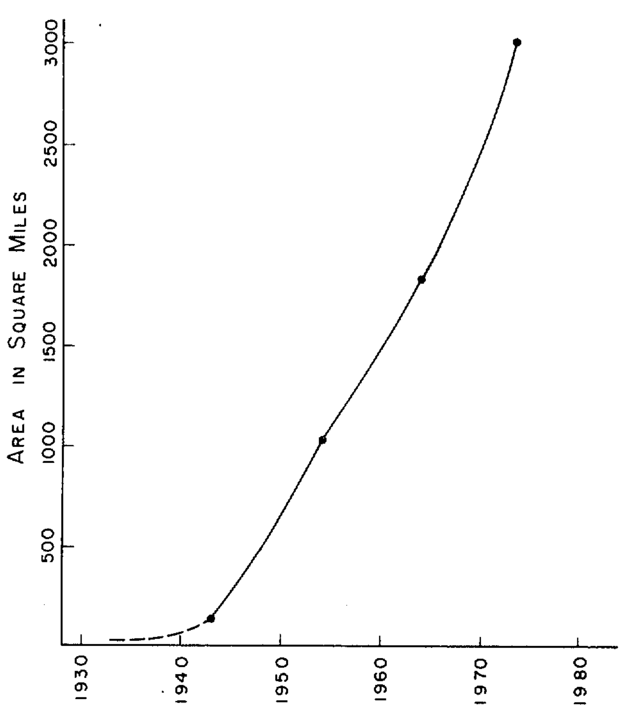


Figure 13. Area in the Texas Coastal Zone impacted by land-surface subsidence in excess of 1 foot between 1943 and 1973. Values are cumulative.

The extent and amount of subsidence are well defined and known through a series of elevation benchmarks established and resurveyed or leveled at selected intervals by the National Geodetic Survey (formerly the U. S. Coast and Geodetic Survey) of the Department of Commerce. The first leveling program was a first-order line from Smithville to Galveston surveyed in 1905 and 1906. In 1918, a first-order line was established from Sinton, Texas, to New Orleans, Louisiana. During the period between 1932 and 1936, several other first- and second-order lines were established, and the two original lines were releveled. In 1942 and 1943, a large number of second-order lines were established and most of the older lines were releveled. Following the leveling program of 1942-1943, subsidence in the Houston area was first documented. Subsequently, releveling surveys were completed in 1951, 1953-54, 1958-59, 1964, and 1973. These surveys clearly establish the extent and amount of subsidence in the lower Texas coastal plain.

Likewise, the cause of subsidence is well documented, primarily through the extensive monitoring of water-well levels, which was started in 1929 by the Water Resources Division of the U. S. Geological Survey. Comparison of areas of water level and piezometric decline with areas of land-surface subsidence clearly shows that they are coextensive. Results of monitoring by the U. S. Geological Survey have been reported in several papers; refer especially to those reports by Gabrysch (1969, 1972), Gabrysch and McAdoo (1972), and Gabrysch and Bonnet (1974) as well as to reports by Marshall (1973) and Turner, Collie, and Braden, Inc. (1966). Portions of this section of the atlas have been drawn from these previously published reports.

Although the principal cause of subsidence is ground-water withdrawal, a minor amount of subsidence can be attributed to natural compactional subsidence, to tectonic subsidence, and locally, to the withdrawal of oil, salt, and sulfur. Subsidence resulting from mineral extraction has been restricted largely to areas of production on and adjacent to certain coastal salt domes. More than 3 feet of subsidence at the Goose Creek oil field was caused by oil production, resulting chiefly from poor production practice in the early history of the field (Pratt and Johnson, 1926).

While the extent, amount, and mechanisms of land-surface subsidence are well documented, methods for mitigating the problem, short of massive curtailment of ground-water pumping, are not evident. Variations in the lithologic composition of the aquifers, as well as local difference in hydrologic behavior, suggest that certain areas are more prone to subsidence than are others.

CAUSE AND MECHANISMS OF LAND SUBSIDENCE

Most of the ground-water production in the Texas coastal plain is from aquifers occurring from near the surface to depths as great as 3,000 feet. The geologic formations involved are composed of varying amounts of alternating sands (the aquifers) and interstratified clays. Significantly, the clays are water saturated and undercompacted; clays nearer the surface are commonly less compacted than those at greater depths. The aquifer sands and interbedded clays dip gently toward the coast; they crop out in a general coastwise-trending belt extending from about 30 to 50 miles inland from the coastline. It is in the zone of outcrop that the aquifers are recharged by infiltration of fresh water. Principal water production is from the Lagarto and Goliad Formations (Evangeline Aquifer), and from the Willis, Lissie, and Beaumont Formations (comprising the Chicot Aquifer). Earlier authors referred to these two aquifers simply as the Principal Aquifer. Similarly, in certain areas of the northeast part of the Coastal Zone, sands above the Principal Aquifer were referred to as the Alta Loma sands or the Alta Loma Aquifer.

Prior to 1900, before heavy pumping commenced, water wells in the artesian aquifers flowed naturally; that is, the aquifers were under sufficient pressure to force water to the land surface within open wells. Subsequent pumping, especially in the past three decades, has resulted in a continuing decline in artesian pressure or piezometric surface over wider and wider areas. Geologists and engineers of the U. S. Geological Survey, who started monitoring water levels in coastal plain wells in 1929, have charted the long-term decline in the pressure levels. In 1943, maximum decline of the water level was about 150 feet; by 1954, the piezometric level had dropped to about 300 feet; by 1964, it had declined to about 350 feet; and in 1974, it locally has declined to 400 feet. Comparison of areas of pressure-level decline and areas of subsidence show clearly their coextensive nature (figs. 14, 15).

The water-saturated clays that occur interstratified with the aquifer sands are compressible and become compacted when subjected to increased load. This reduction in volume of the compressible clays is translated to surface subsidence. Reduction in artesian pressure from pumping causes a loss of buoyant support to the granular structure of the aquifer sands (decreased pore pressure), and each layer is, therefore, subjected to a corresponding increase in effective vertical pressure. This decreased pore-pressure effect is immediately transferred to the contact surface with interbedded clays, but, because of the low permeability of the clays, the clays drain more slowly (fig. 16). The clay layers compress vertically and become thinner; consequently, the overlying sediments and the ground surface subside.

The amount of subsidence that will occur is directly related to the decline in piezometric level, which is a function of the volume of water withdrawn from the aquifer. The amount of subsidence, however, will vary further depending upon the amount of clay within the aquifer section, the vertical distribution of the clay, the compressibility of the clay, and finally, the degree of undercompaction of the clay in its natural state. The amount of clay in the aquifer and the number of clay beds within the aquifer sands, as

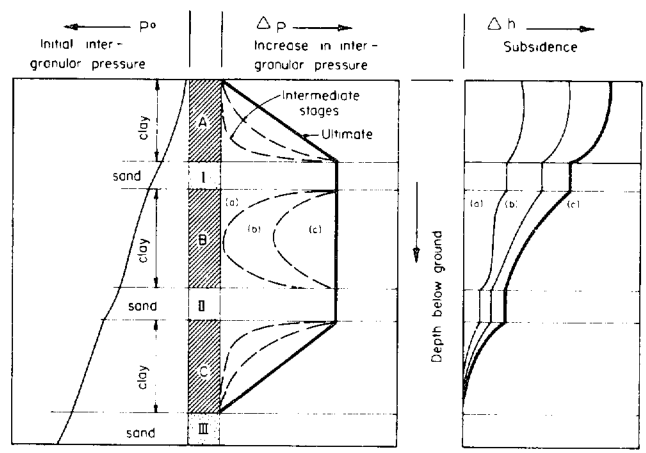
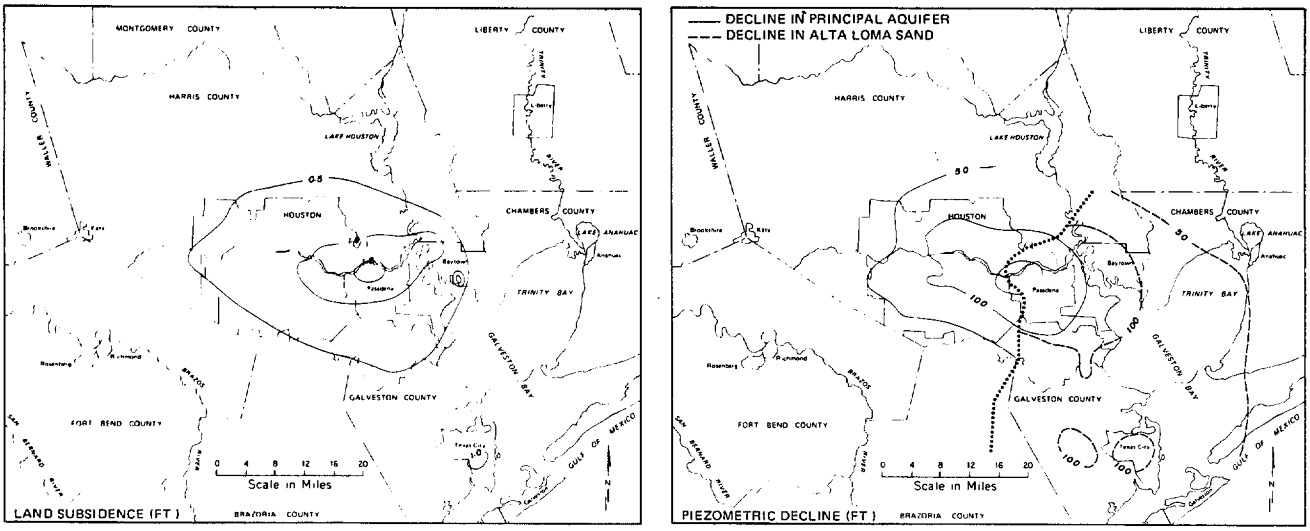


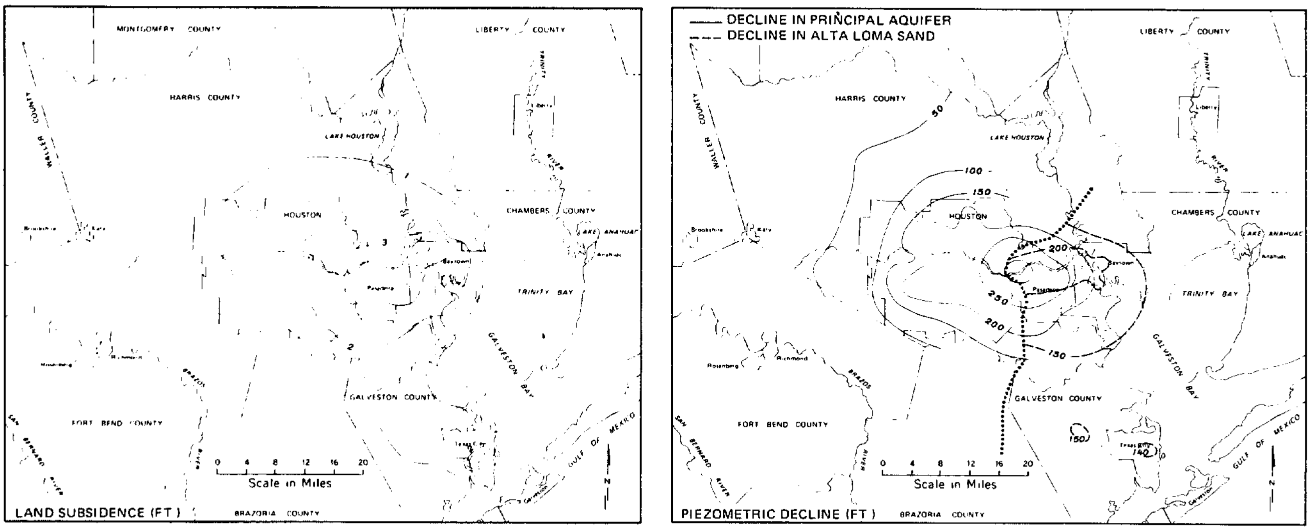
Figure 16. Effects of ground-water withdrawal on intergranular pressure, with consequent volume reductions and surface subsidence. After Turner, Collie, and Braden, Inc. (1966).

well as the compressibility of the beds, vary areally; certain areas are more prone to subsidence than others, even with the same amount of ground-water withdrawal and comparable levels of piezometric decline.

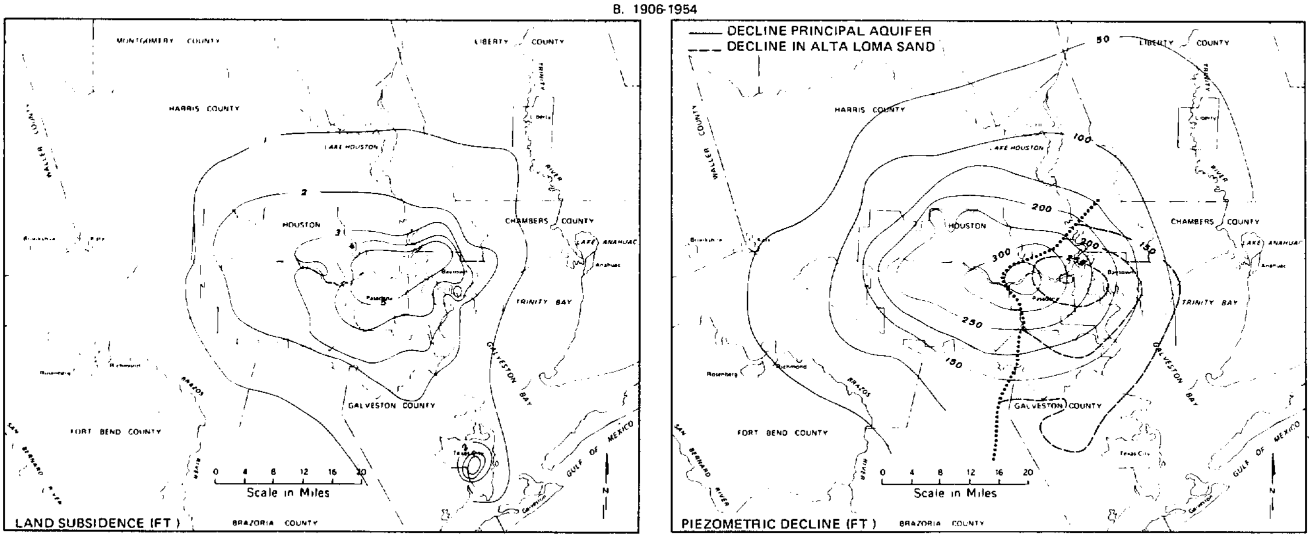
Compaction of the clays and resulting subsidence are nearly 100 percent irreversible (a small rebound may be possible). Further, additional subsidence may occur even if ground-water withdrawal is reduced and the decline in piezometric levels is arrested. This is because of a lag between the addition of the load and ultimate compaction of the clays. Computations by Marshall (1973) indicated that additional subsidence after water-level decline ceases will be at least 50 percent and possibly as much as 150 percent of the subsidence experienced prior to that time. Gabrysch and Bonnet (1974) state that only 15 to 20 percent of additional subsidence will occur. R. O. Kehle (personal communication, 1974), however, suggests that subsidence may stop immediately if piezometric decline is arrested. Variation in the percentage of eventual subsidence, even after arrest of piezometric decline, is also a function of the amount and nature of clays occurring within and associated with the aquifer. Eventual subsidence, therefore, should be variable and will depend on the geologic nature of the aquifer.



A. 1906-1943

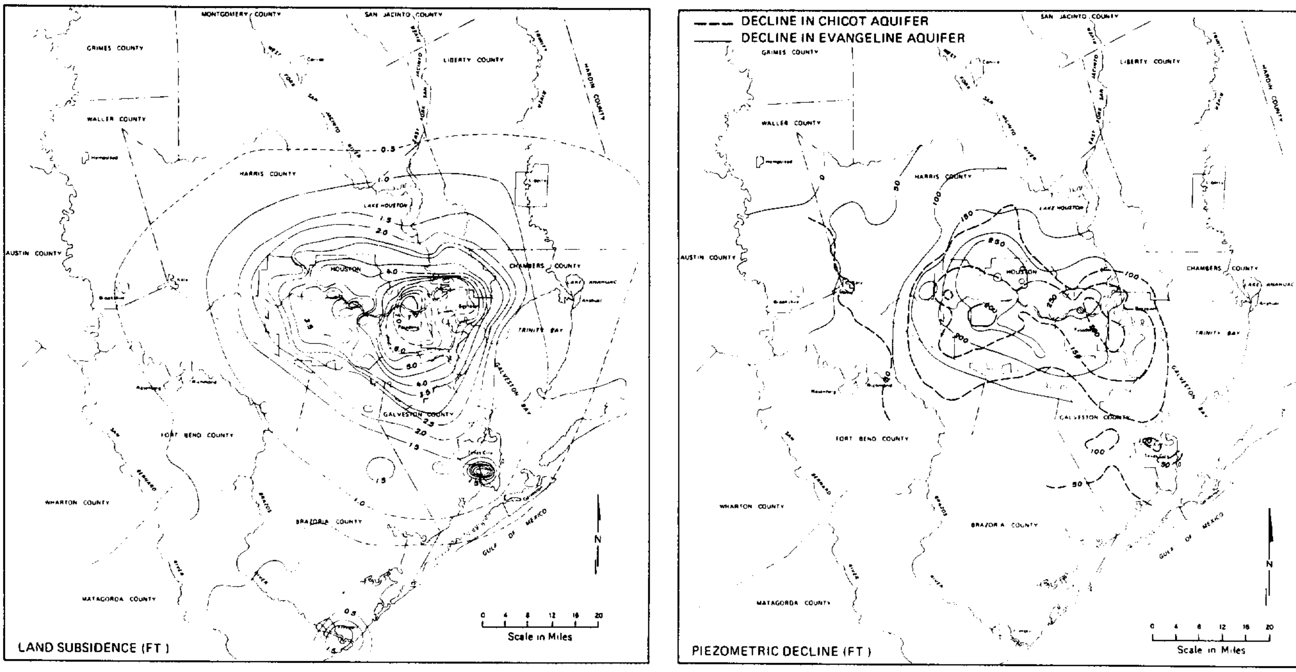


B. 1906-1954



C. 1906-1964

Figure 14. Land-surface subsidence and decline of piezometric (ground-water) surface within Principal and Alta Loma Aquifers, 1906-1963, Greater Houston area. Modified after Marshall (1973).



1943-1973

Figure 15. Land-surface subsidence and decline of piezometric (ground-water) surface within Evangeline and Chicot Aquifers, 1943-1973, Greater Houston area. After Gabrysch and Bonnet (1974).

EXTENT OF LAND SUBSIDENCE

Land subsidence, both in amount of land elevation lost and in area affected, has been increasing significantly during the past three decades. Coincident with accelerating subsidence have been increases in the volume of water withdrawn and decline of artesian pressure levels. In 1943, when releveling recorded the first measurable subsidence, a little more than 140 square miles of land in the Houston region had subsided 1 foot or more, with maximum subsidence of about 1.5 feet. By 1954, about 1,000 square miles of land had experienced subsidence in excess of 1 foot, with maximum subsidence up to 4 feet. In 1964, more than 1,800 square miles of land had subsided more than 1 foot, with maximum subsidence up to 6 feet. By 1974, more than 3,000 square miles of land on the lower Texas coastal plain had undergone more than a foot of subsidence, and maximum subsidence had reached 8.5 feet (Galveston-Houston map). The area of lands impacted by subsidence of 1 foot or more has doubled approximately each decade for the past 30 years. At the present time, about 230 square miles of land, centering on Pasadena, has subsided more than 5 feet.

Measurable subsidence, defined herein as 0.2 foot and greater, now impacts three areas of the lower Texas coastal plain: (1) an extensive area of the upper Texas coastal plain extending from Bay City northward into Louisiana and inland as much as 60 miles (Bay City-Freeport, Galveston-Houston, and Beaumont-Port Arthur maps); this zone includes the critically impacted Greater Houston area; (2) a large part of Jackson County (Port Lavaca and Bay City-Freeport maps); and (3) an area in Nueces and San Patricio Counties centered near the community of Odem (Corpus Christi map). Maximum subsidence in the Corpus Christi area is in excess of 1 foot, with the distribution of subsidence showing a pattern remarkably similar to that of the Houston area in 1943.

Subsidence values shown on the Natural Hazards Maps were calculated with data derived from various releveling surveys conducted by the National Geodetic Survey. Periodic releveling data are limited; therefore, the boundaries between subsidence zones are *approximate*. Three subsidence zones, (1) 0.2 foot to 1 foot, (2) 1 foot to 5 feet, and (3) greater than 5 feet, are based on *maximum recorded subsidence* for any particular benchmark or level station. In some areas, the "total" amount of subsidence has been determined from elevation differences recorded at a benchmark for relatively short periods of time (for example, 1951 to 1973); in other areas with more data, the measured subsidence includes elevation differences recorded for longer periods of time (for example, 1905-1973). This approach of using net or maximum elevation variation at each benchmark provides a map that displays maximum recorded subsidence.

Land subsidence is minimal in the zone of 0.2-foot to 1.0-foot subsidence and has progressed substantially in the zone defined by subsidence in the range of 1 foot to 5 feet. Within the zone of maximum subsidence (greater than 5 feet and, currently, less than 8.5 feet), land subsidence is a factor that requires careful consideration both in urban and industrial development and in maintenance of public facilities. The three zones provide a perspective of the land-subsidence problem consistent with the map scale and goals of the Natural Hazards Maps. The reader may wish to refer to specific studies on land subsidence; e.g., Marshall (1973) and Gabrysch and Bonnet (1974).

PROBLEMS CAUSED BY LAND SUBSIDENCE

The most obvious consequences of land subsidence in coastal areas are actual loss of lands in low-lying tidal areas and submergence of structures along these subsiding coastlines. Equally threatening is the loss of ground elevation and the potential subjection of more land to the natural hazard of flooding, either by hurricane surge or stream runoff. For example, assuming an ultimate subsidence of 10 to 12 feet in the Greater Houston area, it is estimated that approximately 20,000 acres (about 31 square miles) of land may be lost by the year 2000; substantially more land could be lost if ultimate subsidence is greater. Furthermore, if storm tides with the same surge height as those generated by Hurricane *Carla* in 1961 were to strike upper Galveston Bay today (1974), an additional 70 square miles of subsiding lands, much of it extensively developed, would be flooded by hurricane-surge waters.

Depending upon original topography, subsidence can result in change of land slopes, stream gradients, and stream drainage patterns. Changes and reversals in land slope can and have caused problems in such gravity transport systems as water and sewerage lines.

Although land subsidence is regic.ıaı in pattern and is regionally expressed as "bowls" of subsidence, recent studies by the Bureau of Economic Geology indicate that, in detail, subsidence tends to occur in blocks. Such movements are shown by abrupt changes in detailed land-subsidence profiles (fig. 17); a great number of the downward-subsiding blocks shown on these profiles are bounded by active faults. Such faults are posing additional problems for areas of subsidence.

The particular hazard of surface faulting and associated problems is discussed in the chapter, *Faulting*. Subsidence of shoreline lands along the open Gulf and bay shorelines, which can measurably increase the already critical natural hazard of shoreline erosion, has been discussed under *Shoreline Erosion*.

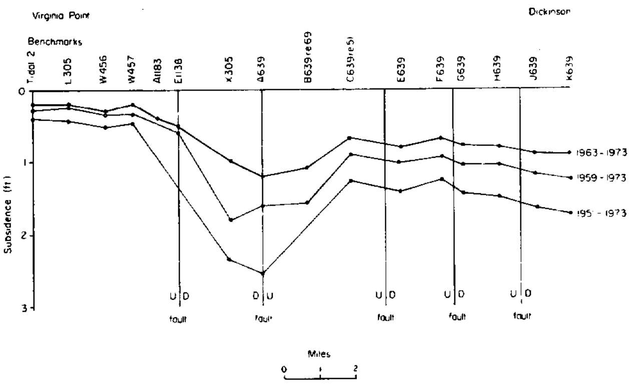


Figure 17. Correlation of active faults with sharp breaks in land-subsidence profiles. Elevation data from National Ocean Survey (formerly U. S. Coast and Geodetic Survey). Profile parallels State Highway 3 south of Dickinson, Texas, Galveston-Houston map area.

MITIGATION OF LAND SUBSIDENCE AND ASSOCIATED PROBLEMS

Although the withdrawal of ground water in the lower Texas coastal plain is the principal cause of subsidence and associated problems, use of ground water has proved to be a significant economic benefit. At the present time, for example, about 650 million gallons per day are withdrawn from aquifers in the Greater Houston area. The cost of ground water is significantly less than the cost involved in transporting and treating surface water. Ground water is, therefore, an important natural resource in the coastal area of the State and its use results in substantial savings to the users. A recent report on the economics of subsidence (Warren and others, 1974) suggests that the total cost of land loss and damage to structures may exceed the cost difference between surface water and ground water. The problems caused by subsidence and ground-water withdrawal must be evaluated in the context of the economic alternatives.

Land subsidence that has occurred in the Coastal Zone is irreversible and, due to lag time in clay compressibility, may continue to a substantial degree, even if pressure-level declines are arrested. Mitigation of the impact already experienced and that which will inevitably be experienced in the future can only be accomplished either by vacating the impacted lands or by constructing protective structures. Of principal concern is the maintenance of lands subject tc water encroachment, particularly those subject to flood inundation. Construction of protective structures is the only means of mitigating the problems of flooding in areas already developed. Several dikes and levees have already been built in critically impacted areas; the elevation of many of these will have to be raised and others constructed. The U. S. Army Corps of

Engineers has investigated the possibility of constructing an extensive hurricane barrier system across the southern end of Galveston Bay; the costs of constructing and maintaining this system can be weighed against its benefits in protection from flooding and inundation. For other areas where subsidence is occurring but where development has not yet taken place, nonstructural methods such as zoning for certain uses might be more feasible.

Finally, the modification of the historical pattern of ground-water withdrawal in the Texas coastal plain can effectively mitigate subsidence and its associated problems. Such a plan will necessarily involve significantly less withdrawal of ground water, but a variety of other mitigating factors should be considered. Different levels of subsidence and associated problems may be tolerated; for example, subsidence is clearly a much greater problem in low-lying, developed areas than it is in less developed areas or in areas at higher elevations. The aquifers, of course, are homogeneous neither in geologic nor in hydrologic character; aquifers with a minimum of intercalated muds can sustain more withdrawal than aquifers containing a large number of undercompacted clay beds. Other mitigating factors include the extent to which associated clays are compressible and the extent to which compression and consolidation have already taken place, both naturally and as a result of ground-water production. Hydrologic variations indicate that certain aquifers can sustain greater ground-water production with less severe declines in artesian pressure than can others. Accordingly, detailed analysis and mapping of the geologic and the hydrologic character of the coastal aquifers might permit delineation of preferred production areas and pumpage levels (natural carrying capacity). This approach could provide the necessary base for determining the maximum amount of withdrawal and the density of producing wells that can exist within prescribed acceptable levels of subsidence. Ultimately, acceptable levels of subsidence or nonsubsidence could be defined, depending on such factors as present state of development and original or present topography or land elevation.

Ground water in the Texas coastal plain is and should be considered a very valuable natural resource. Nevertheless, if subsidence and the several associated problems are to be mitigated, use of ground water, both in water volume and well density, must be adjusted to the carrying capacity of the aquifers. This will require a modification of historical use patterns and most certainly some reduction in the amount of ground water used in given areas, but it need not involve a complete curtailment of ground-water use and withdrawal.

● FAULTING ●

GENERAL STATEMENT

Active surface faults in the Texas Coastal Zone have become an important geologic hazard which daily affects the economic well-being of the people in this area. Active faults severely damage houses, apartment complexes, and industrial plants. Some city streets, farm-to-market roads, and interstate highways must be continually repaired because of fault damage; faults also cross the runways of Hobby Airport and Ellington Air Force Base. Active faults intersect the extensive railroad network at several places, weakening rails, ties, and roadbed, and creating a potential for future derailments.

EXTENT OF ACTIVE FAULTING

Active surface faults are relatively common in parts of the Texas Coastal Zone. Most active faults that have been recognized occur in the Galveston-Houston map area, where 95 linear miles of faulting are shown on the Natural Hazards Map. Many other active faults exist inland from the map area. An active surface fault about 4 miles long also occurs in the Corpus Christi map area. There are 96 miles (table 1) of known active faults in the entire area covered by this report; locations of the faults have been compiled from studies by other workers (Weaver and Sheets, 1962; Van Siclen, 1967; Sheets, 1971; Reid, 1973; Clanton and Amsbury, 1974) and as the result of recent mapping in this region by the Bureau of Economic Geology. More detailed mapping in the future will undoubtedly locate more faults, and possibly may discount some faults already mapped. In addition, new faults may be generated in areas of land-surface subsidence.

IDENTIFICATION OF ACTIVE FAULTS

Active faults are defined as faults which have had movement since the end of the Pleistocene (ice age) about 20,000 years ago. Most of the faults shown on the Natural Hazards Maps, however, have moved in the last 30 years.

Four lines of evidence have been used in this atlas to identify active faults: (1) breaks in street pavements, foundations, highways, airport runways, and swimming pools involving vertical displacement (cover photograph); (2) topographic scarps defined by an abrupt steepening of land surface along uniform slopes or flat areas; (3) sharp breaks in rates of subsidence as determined from cumulative topographic profiles; and (4) linear tonal anomalies on black-and-white and on color-infrared aerial photographs. All active faults shown on the Natural Hazards Maps have been verified by ground observation; most of these features have not been subjected to subsurface analysis.

The presence of cracks in highways and structures, coupled with evidence of continual repaving of highways or repairing of buildings, is an excellent guide for locating active faults. This type of evidence is considered the most reliable because it shows the precise location of the surface expression of the fault and indicates that the fault is presently active. A fault crossing a parking lot at Ellington Air Force Base is shown on the cover of this atlas; this fault also extends across the runways, causing extensive, continuing damage to the landing surfaces.

Changes in the elevation of survey benchmarks can also be used to delineate location and amount of movement along faults. Topographic profiles break sharply across active faults. A subsidence profile, based on cumulative, first-order topographic leveling data from Virginia Point to League City (along State Highway 3 in Galveston County), is one of several such profiles that shows changes in topographic slope at the intersections of level lines and faults (fig. 17). This technique is capable of pinpointing very slight changes in differential subsidence; the only drawback to the method is that the benchmarks are generally located a mile apart; this distance precludes a precise location of the active fault with the level profile.

Low topographic scarps may show the exact location of a fault, but it is difficult to determine if the fault is presently active or inactive. The continuation of such topographic scarps into a continually cracking highway pavement nearby does confirm, however, the recent activity of the fault.

The least confirmatory method for locating faults is the identification of linear tonal anomalies on black-and-white and on color-infrared photographs. Nearly all active faults can be identified on aerial photographs, but not all linear tonal anomalies are active faults. Aerial photographs are a very important tool, however, because they identify areas where more intensive ground study should be conducted. Several of the active faults on the Galveston-Houston area map were initially identified by this technique and later substantiated by field work.

GEOLOGIC CONTROLS OF FAULTING

Mapped surface faults and the surface trace of subsurface faults that are projected to the land surface exhibit a strong parallelism. At this time, however, there are only a few cases for which sufficient data are available to reliably connect the surface-expressed fault with a verified subsurface fault. Two such examples are the Addicks fault in the Fairbanks oil field northwest of Houston (Van Siclen, 1967) and the Clarksville fault in the Saxet oil field west of Corpus Christi (Poole, 1940). Both of these faults can be traced to depths of 7,000 feet. The Saxet fault is shown on the Natural Hazards Map of the Corpus Christi area. The Addicks fault occurs immediately northwest of the Natural Hazards Map of the Galveston-Houston area.

Several linear tonal anomalies, along which there has been no perceptible fault movement, also correlate with subsurface faults. Subsurface faults extrapolated to the land surface in the Angleton oil field, the Blessing oil field, and the West Columbia oil field generally coincide with both location and orientation of linear tonal anomalies. The lack of detailed well control and seismic data, however, prevents a definitive conclusion that, in these cases, the surface lineation and subsurface fault are in fact coincident.

The similarity in trend of surface and subsurface faults indicates that most surface faults are probably genetically related either to long-trending coastwise fault systems extending upward from several thousand feet below surface and/or to faults associated with the numerous salt domes of the area. Faults radiating from salt domes may explain why some surface faults trend perpendicular to the common coastwise trend. Where verified, the association between surface and subsurface faults indicates that some surface faults are products of natural geologic processes.

Faults of the Coastal Zone have been explained by a number of processes: (1) deposition of sediments (Carver, 1968); (2) upward movement of salt masses to form salt domes (Quarles, 1953); (3) gulfward creep of the coastal landmass (Cloos, 1968); and (4) bending of the landmass due to regional tectonics. Sediment loading, salt movement, and gulfward creep are probably the dominant causes for fault development in the Coastal Zone. Sediment accumulation in the present-day Gulf Coastal Zone, however, is occurring principally in the area of the Mississippi delta; there is little evidence to document continued growth in the salt domes or a natural gulfward creep of unconsolidated sediments.

METHODS OF FAULT ACTIVATION

Faults in the Texas Coastal Zone are products of natural geologic phenomena. Geologic evidence suggests that fault activity today should be a relatively minor process. The frequency and activity of fault movement, nonetheless, is increasing. There are clear indications that certain of man's activities, such as ground-water withdrawal and oil and gas production, are causing this increase in fault activation. In the Houston-Galveston-Baytown area, where there has been heavy withdrawal of ground water, oil, and gas and extensive concomitant subsidence, several faults have become active. Nearly all faulting has occurred in areas where the potentiometric surface (piezometric surface) has dropped over 100 feet and where there has been at least 1 foot of land-surface subsidence (Galveston-Houston map). Of course, these areas of heavy ground-water usage are also the areas of greatest land use and, hence, the presence of active surface faults and their effect is more likely to be noticed than in areas of less intense use.

The monitoring of movement on the Long Point fault and the Eureka Heights fault in western Houston shows a direct correlation between vertical fault displacement and change in the potentiometric (piezometric) surface of the Chicot Aquifer (fig. 18). In March of each year, when the potentiometric surface begins to drop, movement along the Long Point fault becomes more rapid. In October, when ground-water pumpage decreases, the potentiometric surface rises and the rate of fault movement decreases. Some rebound even occurs on the Eureka Heights fault.

Faults are being activated by natural as well as man-induced phenomena. The Long Point fault in western Houston appears to be moving for normal geologic reasons and because of man-induced phenomena. A topographic map with a 1-foot contour interval, surveyed before 1920, shows a topographic scarp coinciding with the location of the Long Point fault (Van Siclen, 1967). The curve of the fault displacement for the Long Point fault (fig. 18) at section *a-a'* shows movement even though there is decreased ground-water production and a rising potentiometric surface, possibly indicating a natural method of activation.

Man-induced fault movement may occur by two different mechanisms: differential consolidation of sediments and landslide-type failure caused by vertical seepage forces. *Differential consolidation of sediments* can occur (1) if there is more mud on one side of a fault than on the other because of a *facies change*, or (2) if the fault acts as a *hydrologic barrier* to fluid migration. The amount of land-surface subsidence by consolidation of sediments depends, in part, on the amount of compressible clay associated with a sand aquifer. Many growth faults in the subsurface of the Gulf Coast area are located at major *facies boundaries*, separating, for example, prodelta muds from deltaic sands. If growth faults were active during the Pleistocene, they may have caused appreciable facies variations in the Chicot Aquifer. An equal lowering of the potentiometric surface across a fault with different clay-sand ratios (facies) on either side will result in different amounts of consolidation and differential land subsidence.

The amount of land subsidence at any particular point is also controlled by the amount of decline in the potentiometric surface, as well as by the amount of mud within the aquifer system. If a fault acts as a *hydrologic boundary* and causes the potentiometric surface to be at different elevations on either side of the fault, there will be different amounts of consolidation that may be expressed as fault movement at the land surface.

Vertical displacement on the Eureka Heights fault demonstrates fault activation by differential consolidation of sediment (fig. 18). The rebound of vertical displacement shown on the graph can be explained by the slight expansion of elastic sand bodies within the aquifer on only one side of the fault. Rebound can occur if there is a hydrologic boundary or if there is a significant lateral change in the composition (facies) of the aquifer.

Faults may also be activated by increasing the overburden pressures (vertical effective stress), resulting in a *landslide-type failure.* If the Gulf Coast sediments are treated as a large landslide, they are unstable with a factor of safety less than 1.0 (Reid, 1973). The Coastal Zone theoretically should be slowly sliding into the Gulf of Mexico. An increase in effective overburden pressures (analogous to loading at the head of a landslide) should cause the unstable mass of sediments to move more rapidly toward the Gulf of Mexico and initiate an increase in active faulting.

An increase in effective overburden pressure is accomplished by dropping the potentiometric surface in an artesian aquifer. The downward flow of water from a shallow, unconfined aquifer and overlying aquitards to the artesian aquifer transfers some of its energy to the sediments through frictional lag, causing an increase in the effective stress in the direction of ground-water flow. This increase in stress is known as "seepage pressure." The effective overburden pressure in a static system at any particular point in the subsurface is approximately equal to the bouyant weight of the sediments. The additional seepage is equal to the decline in the potentiometric surface times the unit weight of water (Lofgren, 1968). For example, at a depth of 400 feet, the effective overburden pressure is equal to approximately 170 pounds per square inch (psi). A drop in the potentiometric surface of 200 feet will cause an additional effective overburden pressure of 86 psi or a 50-percent increase in the effective overburden pressures, which would be the same as depositing an additional 200 feet of saturated sediment over the Houston and Baytown area. In some places in the Houston area, the potentiometric surface has dropped over 400 feet. This increase in overburden pressure may be enough to activate some faults in the Gulf Coast sediments.

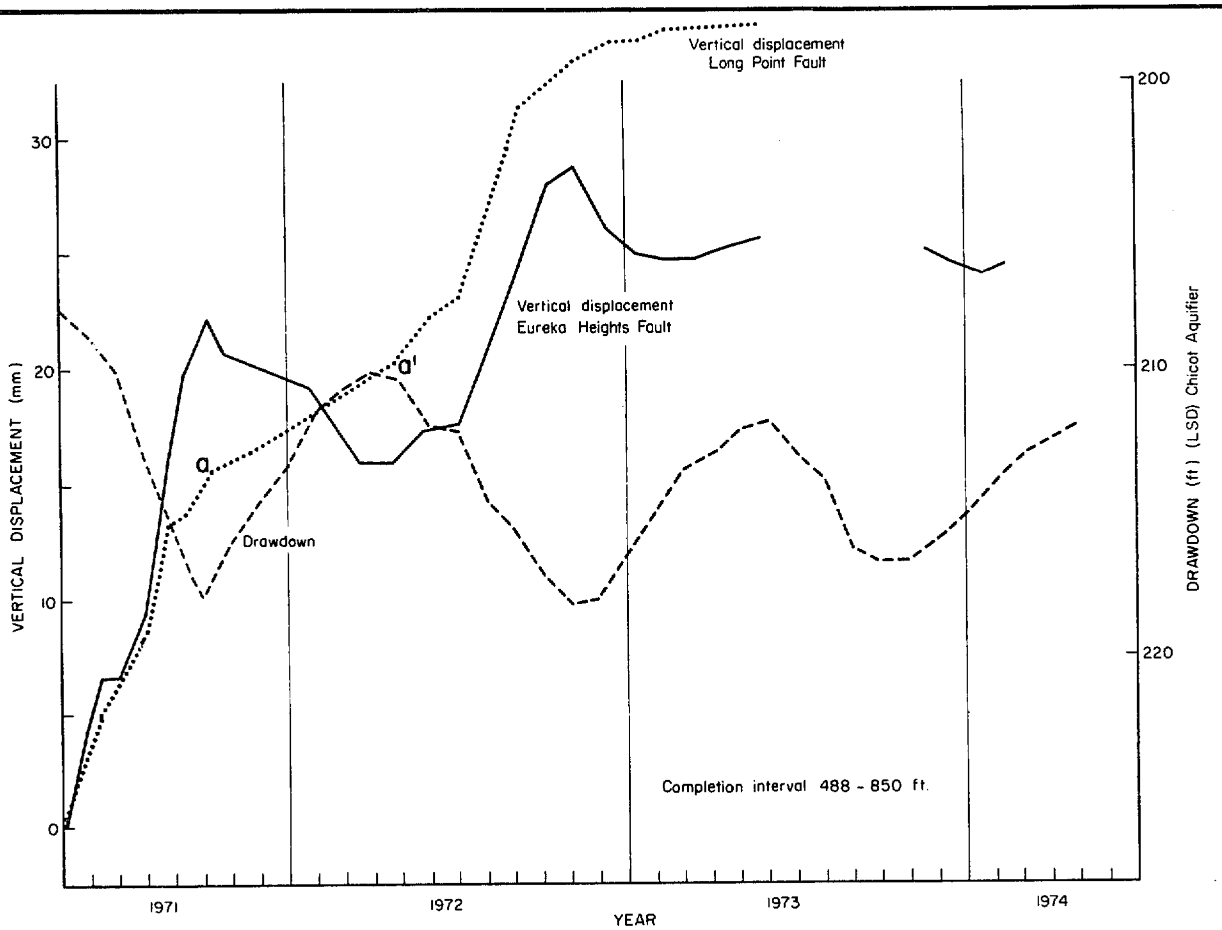


Figure 18. Vertical displacement on Long Point and Eureka Heights faults in western part of Houston compared to drawdown of piezometric surface of Chicot Aquifer. Displacement data for April 1971 to April 1972 from Reid (1973); displacement data for May 1972 to January 1974 and drawdown data for piezometric surface for federal observation well LJ-65-13-408 from R. Gabrysch (personal communication, 1974).

Natural movement, differential consolidation, and landslide-type failure are all important mechanisms for fault activation; their relative importance in the Texas Coastal Zone has not yet been determined. Fault activation by oil and gas exploitation has also been documented in the Texas Coastal Zone. Pratt and Johnson (1926) observed fault activation in the Goose Creek oil field. The Clarkwood fault west of Corpus Christi, which exhibits a 4.5-foot scarp, was probably caused by oil production from the Saxet oil and gas field. The extensive faulting over the Clear Lake oil field also may have been caused by oil production.

MITIGATION OF PROBLEMS ASSOCIATED WITH FAULTING

One of the purposes of including the trace of active faults on the Natural Hazards Maps of this atlas is to help explain the reason for continual repair problems in particular areas (e.g., highways, city streets, and train tracks) and to delineate those areas where special care may be required in future development. It stands to reason that man-made structures should be built with full knowledge of potential foundation problems.

Another related problem is the distance a structure should be built from a fault. Along some faults, the scarp (the topographic expression) is narrow, perhaps less than 30 feet wide, such as the fault in the town of Hitchcock. Structures can be located safely in close proximity to these kinds of faults, especially when special engineering techniques are applied. Other faults have relatively wide scarps. For example, the topography in the area of the Long Point fault where it crosses Memorial Drive in western Houston appears to be altered up to 150 feet on either side of the fault (Reid, 1973). Construction of large, heavy structures should be carefully designed for or perhaps even eliminated from this wide zone, whereas light structures, such as houses, may not be adversely affected. The width of these hazardous zones needs to be evaluated for each fault. Because the coastal plain is so flat, unlevel land adjacent to an active fault is probably an indication that the area is being affected by recurring fault movement. Subtle variations in topography can best be determined by measuring the change in slope with surveying equipment. These slight variations can also be determined by detailed analysis of benchmark-level data.

The rate of movement along a Coastal Zone fault is another factor of importance to the people of the region. The sudden movement along a California-type fault produces earthquakes and does extensive damage to areas not even close to the active fault. Fault movement in the Texas Coastal Zone, however, is gradual, and earthquakes are *not* a hazard. The amount of surface displacement that can be recognized on the Coastal Zone surface faults ranges up to as much as 40 feet at the Hockley scarp northwest of Houston. This accumulated displacement has, however, occurred over a long period of time predating man's settlement of the Coastal Zone. Most fault scarps in the Coastal Zone are no more than a few feet high. In Houston, the average rate of displacement has been estimated to be 1.3 inches per year (Reid, 1973). It is feasible to build structures across these faults as long as they are designed so that engineering techniques can compensate for differential offset.

Faults of the Texas Coastal Zone need not be a problem. Future construction on faults can be avoided, and where this is impossible, the awareness of faults will permit architects and engineers to design structures that can accommodate the low rates of differential movement. Decreased ground-water usage may tend to deactivate many of the faults (fig. 18). Technically, this method of fault mitigation is possible.

CONCLUSIONS

A number of natural hazards affect the Texas Coastal Zone. Some of these hazards are actually increasing in magnitude, but the impact of all hazards obviously becomes more critical with increased development in the Coastal Zone. The degree of impact and the damage and loss resulting from natural hazards depends upon the particular use made of hazard-prone lands. Mitigation of the impact of natural hazards can lead to significant reduction of losses currently sustained or likely to be sustained in the future.

Clearly, the first step in mitigating the effects of natural hazards is adequate and comprehensive delineation of hazard-prone lands and of processes that give rise to the hazard. "Natural Hazards of the Texas Coastal Zone" is a first effort in delineating hazard-prone lands and in attempting to explain, with current knowledge, the processes leading to the hazard. Second, the present and projected use of hazard-prone lands needs to be determined and inventoried. Third, hazard impact, in terms of frequency, extent, and severity, can be assessed in terms of the relation of costs to benefits. Special attention needs to be directed to those natural hazards that may pose a threat to life or property. Cost-to-benefit analysis can also be applied to determine whether it is feasible to undertake technological and engineering programs aimed at mitigation. For hazard-prone lands already developed, the construction of hazard prevention structures is the only recourse in hazard mitigation; for hazard-prone lands that have not been developed, a variety of alternative measures may prove to be both economical and appropriate.

In a recent study by the California Division of Mines and Geology (Alfors and others, 1973), the total projected loss to the State of California from natural hazards over the period 1970 to 2000 is estimated to be $55 billion. While California has some hazards not common to Texas, such as earthquakes, Texas experiences some natural hazards that do not occur in California. Importantly, the California report estimates that $38 billion of the $55 billion loss, or about 70 percent, can be prevented by applying current state-of-the-art loss reduction or hazard mitigation measures. These measures include technological and engineering approaches, as well as methods involving zoning and preventative planning. Further, these hazard mitigation measures can be applied at a cost of $6 billion over the 30-year period. A comparable overall cost-to-benefit ratio generally would be applicable in the Texas Coastal Zone. In addition to satisfying the need for increased public safety and fulfilling the social and political requirements, natural hazard reduction and mitigation is simply good business.

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SECTION III

HAZARD ZONE DELINEATION FOR STANDARDS AND CODES

The principal purposes of the effort reported in this volume are to develop minimum performance criteria for structures located in high-hazard coastal areas and to draft a model building standard that can be readily incorporated into common existing building practices. From the beginning it was obvious that it would be necessary to define specific hazard zones on the basis of the degree of exposure to destructive processes, and to develop standard requirements for each zone.*

The standards and model building code presented in the following section are designed to provide a reasonable chance for survival of buildings during the occurrence of a hurricane. Any structure built to the code is likely to survive, but an extra margin is provided for high-rise structures that could be used for safe refuge, i.e., vertical evacuation of residents. For high-rise buildings, specific requirements are given for the skin or cladding, since these are of utmost importance if the building is to be used for safe refuge.

THE TEXAS DESIGN HURRICANE

Before looking at the zone delineation process, it is necessary to determine what parameters are most likely to be associated with the occurrence of a "probable" hurricane. Many approaches exist for statistically estimating hurricanes of specific recurrence intervals, and for classifying them as minor, major, or great hurricanes. Section II, "Natural Hazards of the Texas Coast," contains a detailed discussion of these approaches. Some federal agencies have used the concept of standard, project or probable maximum hurricanes. These classifications differ among agencies, mostly because the different agencies have different missions and thus are concerned about different effects.

For the purpose of this report--the development of model minimum building standards--a mixture of the likely forces taken from federal agencies' definitions of typical hurricanes, tempered

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* *Since this hazard zone delineation process is vital to correct application of the model standard, this entire section should be distributed with any copies of the model standard.*

by the judgment of a panel of experts, is combined to give the Texas Building Design Hurricane (TDH). This hurricane is severe enough to warrant consideration in building standards and occurs frequently enough to make the use of more rigid standards than those presently being used economically feasible. It is expected to generate the following sources of potential damage:

- WIND: maximum windspeeds (fastest mile) up to 140 mph at a height of 30 feet, increasing with height in accordance with the one-seventh power law to a maximum about 300 feet above the surface for open coastal areas. Peak gust speeds will exceed the sustained values by varying percentages as given in the wind load section of the code. (In general, gust percentages will decrease with height increase.)

- HURRICANE TIDES (three sources of potential damage):

  1. SCOUR due to currents and wave action, including washovers;

  2. BATTERING due to waterborne debris;

  3. FLOODING due to combinations of rises in sea level from storm surge and inland runoff from heavy rains and riverine discharges.

HURRICANE HAZARD ZONES

An analysis of the processes and forces associated with a hurricane; extensive examination of empirical damage data; and a thorough knowledge of the geological, hydrological, and topographical characteristics of the Texas coast leads to the identification of four distinct coastal hazard zones.* These are shown in Figure III-1. Ranging from most to least severe, they are

ZONE A:
1. 140 mph sustained winds;
2. scouring action affecting foundation design;
3. battering due to waterborne debris.

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* *For further discussion of specific damage mechanisms, see Section II of this report; U.S. Army Corps of Engineers Hurricane Damage Survey Reports; and NOAA's damage assessments.*

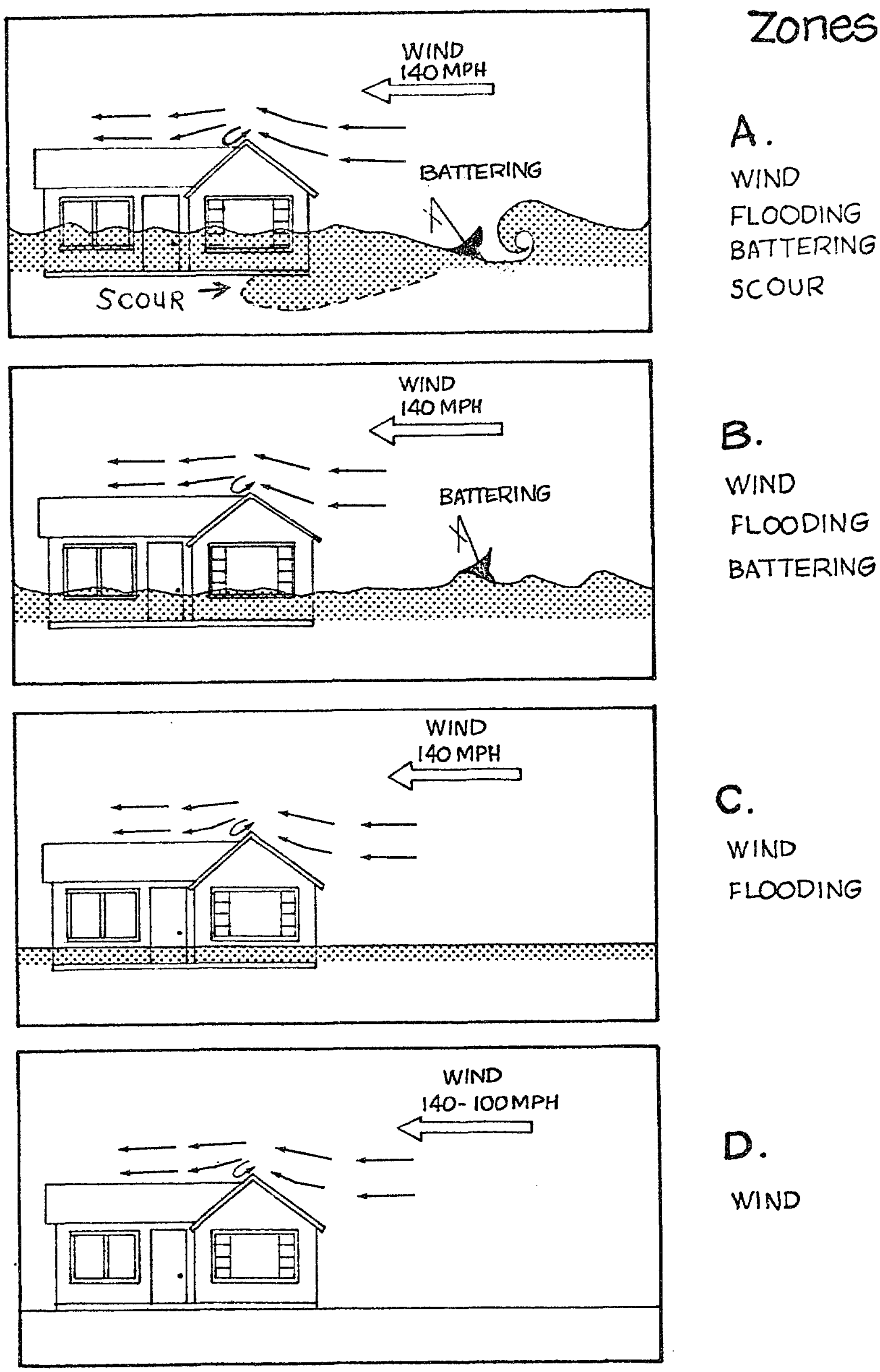

FIGURE III-1
(SAME AS FIGURE I-2)
SCHEMATIC REPRESENTATION OF HAZARD ZONES A TO D IN TEXAS COASTAL AREAS.

4. flooding (still water levels from expected hurricane inundation more than one foot above building grade level).

<u>ZONE B</u>: Same as Zone A except without scour.

<u>ZONE C</u>: Same as Zone A except without scour and battering.

<u>ZONE D</u>: 140 mph sustained winds at C-D boundary, diminishing inland as an inverse function of distance to 100 mph.*

COMPUTATION OF HAZARD ZONES

For regular coastlines without barrier islands, embayments or estuaries, the four hazard zones will comprise a family of narrow strips paralleling the coast. The inland extent of each is normally a function of the height of the storm tide hydrograph at the open coast, the topography of the coastal plain, and the rainfall runoff associated with the hurricane.

When barrier islands and large estuaries are present the inland flooding and the disfiguration of otherwise uniform hazard zone strips is influenced by (1) barrier islands which impede volume transport of surge water inland, (2) the additional component of surge (wind setup) due to wind stresses on shallow water surfaces in estuaries which in turn is a function of (3) the bathymetry and geometry of the estuary, (4) the size and rate of movement of the hurricane, (5) the rainfall runoff and riverine discharges (fresh water), (6) the initial rise of salt water (1-3 feet) in the estuary (forerunner tide), often arriving more than 24 hours ahead of the storm center, (7) the tendency for seiching action as the hurricane moves inland, and (8) the usually smaller increments (on the Texas coast) contributed by astronomical tides and wave setup.

There is no general two-dimensional model for use in bays or estuaries to compute numerically the total inundation

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* $V_D = 100 + \frac{40}{1+d^2}$, *where* V_D = *wind speed in Zone D*

d = *distance inland from C-D boundary*

potential across inland bay shores.* Most models with enough physics incorporated to accomplish this are either adapted to the bathymetry of a single shallow estuary, or otherwise compute in one dimension the inundation along a single line or transect inland from the coast. To model, in two or more dimensions, the scope of inland flooding for a single bay area is a very expensive and time-consuming task, and the results apply only to that area. What is needed is a reasonable, conservative approximation procedure which can be used quickly and inexpensively by competent engineers, and which will always yield the same results.

The method and alternative specific procedures described in Annex C meet these requirements. It is a general method, physically founded, that can be applied quickly and inexpensively by qualified engineers. It is sufficiently objective to yield repeatable results, and precise enough to use for determining the hazard zone of a particular structure and for establishing the appropriate building standard/code.**

*PRIMA FACIE FACTORS IDENTIFYING HAZARD ZONES****

Irrespective of the flood levels computed for a building site using the procedures described in Annex C, the following physical exposures will be overriding in determining in which zone a particular site is located.

I. <u>ZONE A. Areas of washover and scour:</u>

a. Narrow, low segments of barrier islands and peninsulas that are generally breached as a

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* *A quasi-two-dimensional model has been applied to individual bays and estuaries of some portions of the Texas coast by the U.S. Army Corps of Engineers based upon work by Reid and Bodine (1970), and work is in progress on similar models elsewhere. However, each bay poses a separate modelling problem, and the output comprises only the surge component of tidal flooding, not the freshwater contributions or the initial rises, which on the Texas coast may be considerable.*

** *A technical paper by Drs. Simpson and Freeman, who developed the procedure, is available through the Texas Coastal and Marine Council for those wishing to explore the theory and mathematics of the procedure.*

*** *As used herein, "prima facie conditions" refer to physical evidence--meteorological, geological, topographical, or hydrological--which may be in disagreement with the analytical results. In such cases, the specified prima facie evidence will govern.*

result of elevated water levels during hurricanes or tropical storms will be classified as Zone A. Such areas include much of Bolivar Peninsula in the vicinity of Bolivar Bay, Matagorda Peninsula east of Green's Bayou, the southern end of San Jose Island, and South Padre Island. Other coastal areas having experienced or presently holding a high potential for washover (breaching) during a hurricane will also be classified as Zone A. Sources for the identification of such areas include the Bureau of Economic Geology, the University of Texas at Austin.

b. A zone extending between Gulf beaches and a line at least 300 feet inland from the maximum elevation immediately adjacent to the beach (e.g., dune crest or crest of sand and shell ramp) will be classified as Zone A.

c. A zone along low-lying (less than 10 feet) unprotected (nonbulkheaded) bay shorelines, extending at least 200 feet inland from the highest elevation near the shoreline will be classified as Zone A.

d. Areas within 200 feet of unprotected (non-bulkheaded) navigation channels on peninsulas and barrier islands will be classified as Zone A.

e. Areas with a sand substrate subject to hurricane flooding greater than 3 feet in depth and with expected water current velocities greater than 3 feet per second for one hour or more during the rise or fall of the surge will be classified as Zone A.

II. ZONE B. Battering:

In the absence of washover channels and extensive scour, battering from waterborne debris will be expected to occur and will comprise the basis for defining Zone B under the following situations:

a. On barrier islands and peninsulas a zone of flooding extending inland from the most landward foredune or ridge line to the boundary of Zone C, or on low-lying bay shorelines having primarily clay substrates, a zone extending inland from the shoreline at least 500 feet regardless of building density.

b. In areas where hurricane flooding is expected to be greater than 4 feet, building density is not greater than one major structure per acre, and fetch is considered to be the distance a wind of constant direction travels without interruption or diversion over a water surface.

III. <u>ZONE C. Wetting:</u>

In the absence of the above conditions, but where still water hurricane flood levels are in excess of one foot, the area will be designated as Zone C.

IV. <u>ZONE D. Wind Only:</u>

Zone D is concerned only with wind forces on structures, primarily the dynamic loads. The problem in defining the inland extent of unusually severe hurricane winds and thus the width of Zone D is that the rate at which winds of design speed at the coast diminish is less a function of the roughness of the terrain than it is of the baroclinity* of the environment into which the hurricane moves as it passes inland. If a hurricane retains the barotropic** environment which attends it most of its life over ocean areas, the loss of energy flowing from sea to air will rob a hurricane of its hurricane force winds in a few hours after it crosses a coast. If, however, it encounters a baroclinic environment, especially one which accelerates the outflow at the top of the cloud system, it may retain winds of 75-100 mph great distances inland--e.g., in Hurricane Hazel, 1954, and to a lesser degree, Hurricane Agnes in 1972. However, there are no examples of hurricanes maintaining such extreme winds as 140 mph observed at ocean or bay shores more than a few tens of miles inland. Therefore, Zone D is arbitrarily defined as an area in which the wind at the C-D boundary is 140 mph, but diminishes to 100 mph as an inverse function of distance inland from the C-D boundary***, to a minimum of 100 mph. In this specification

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* *Baroclinity - a property of the atmosphere characterized by large horizontal temperature variations. Energy from baroclinic sources sometimes succeeds in accelerating movement of air flowing out of the top of hurricanes, and thus the flow of air through the hurricane, keeping it strong after it loses its initial barotropic energy sources.*

** *Barotropic - a condition characterized by very small temperature gradients and one in which the sources for the development of storms depends primarily upon the release of heat from the growth of cumulus clouds. This condition is essential to the formation of hurricanes and for the growth which characterizes most of their life cycle.*

*** $V_D = 100 + \frac{40}{1+d^2}$, *where* V_D = *wind speed in Zone D*
d = *distance inland from C-D boundary*

it is acknowledged that large variations around these figures will occur from hurricane to hurricane. In a few cases even small interior areas of barrier islands may be classified as Zone D where elevations are substantially above 20 feet MSL and the soil is stabilized from erosion.

DOCUMENTATION OF HURRICANE-RELATED PROCESSES AND ATTENDANT DAMAGE IN ZONE A

From the standpoint of coastal planning, Zone A is the most critical zone for building design. It is also the most readily identified hazard zone in the field and on aerial photographs because of the distinct alteration of the landscape by strong currents and wave action. Extensive coverage of aerial photographs taken immediately following Hurricanes Carla, Beulah, and Celia provide sufficient information for the delineation of washover channels as defined above.

The damage from Hurricanes Carla, Beulah, and Celia is well documented in other reports (U.S. Army Corps of Engineers, 1962, 1968, 1971; Brown and others, 1974; Hayes, 1967; McGowen and others, 1970), but the principal cause of damage from each storm (surge, aftermath rainfall, wind) exceeds the equivalent characteristics of the design storm used to determine the extent of hazard-prone areas. On the other hand, data on dune retreat and shoreline changes are available for other storms; for example, the 1949 hurricane (aerial photographs) and Hurricane Fern (beach profiles). From these and other field data we can determine the maximum and average beach scour and dune retreat. These figures can then be used with other physical parameters to determine the projected limits of areas affected by hurricane-related processes.

Several storms have caused beach erosion and dune retreat of 50 feet or more. Maximum shoreline erosion documented on the Texas coast occurred during Hurricane Carla when a segment of Matagorda Peninsula retreated 600 feet (McGowen and Brewton, 1975).

Dune retreat and shoreline erosion produced by surge from Carla were of extraordinary magnitude in the area affected by the right semicircle of the storm. Fortunately, there was no residential or commercial development near the site of landfall on Matagorda Peninsula, for many buildings would have been destroyed. Recently, a storm less intense than Carla (Hurricane Eloise, September 1975) struck the Florida coast and caused extensive damage. Building foundations were undermined and superstructures collapsed as a result of beach scour and dune retreat (Morton, 1976).

The fixed distance (300 feet) representing the landward boundary of Zone A was selected primarily for a pragmatic reason: the constant distance facilitates the hazard zone identification process. Otherwise, it would be necessary to develop a complicated procedure whereby the probability of storm occurrence for a given time period and coastal segment would be used with an average value of dune retreat per storm to determine, in conjunction with dune characteristics, a theoretical dune erosion value which then would be used with a margin for indeterminants to define the landward boundary of Zone A. In essence, the value of 300 feet represents an estimate of dune retreat that might be expected over a long period with the probability of a hurricane every 11 years, and the probability of a great storm every 29 years. Historical records indicate that the cumulative effect for a long period would be about 200 feet with a margin of safety of 100 feet. This does <u>not</u> suggest that scour will <u>not</u> occur 300 feet inland from the dune crest, but rather that the probability of such an event is rather low.

ALTERNATIVE BOUNDARY SELECTION--ZONE A

In many respects, the beach and washover areas described in preceding sections are similar to Zone V (velocity) on the FIA flood maps.* There are, however, minor differences in the boundaries. For example, the FIA maps exhibit straight line boundaries which do not conform to the topography. In contrast, the boundaries proposed for the hurricane hazard zones are controlled largely by the topography; therefore, mapped boundaries for Zone A would not be straight lines but would be dependent on the configuration of the dunes and washover areas. Another difference in approach is that the FIA maps emphasize elevation whereas the hurricane hazard zones emphasize distances on the ground.

PEAK STORM SURGES

A major input to the zone determination is an estimate of the peak storm surge and flooding levels at the open coast and at bay shores. Too often it is assumed or concluded that the highest surges always occur at the open coast directly exposed to the sea. Factually, the ratio of surge heights at the open coast to those on bay shores depends upon the speed, size and direction of approach of a hurricane. A severe slow-moving hurricane can cause much higher flooding at bay shores many miles from the open coast than at the

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* *Those maps issued by the Flood Insurance Administration that define their categories of floodplain.*

coast itself. For example, in Hurricane Carla, 1961, the maximum surge height on the Gulf front of barrier islands was approximately 15 feet, but near Port Lavaca, 23 miles away, the surge exceeded 22 feet. On the other hand, a storm moving inland at moderate speeds may cause surges of equivalent height at both open beaches and bay shores far inland, and a rapidly moving hurricane will cause greater tides at the open coast. The selection of a design hurricane needs to provide an equitable balance between these possibilities, and the methodologies used to define the Texas Design Hurricane addressed this problem.

The profile of peak open-coast surges for the Texas Design Hurricane is presented in Figure II-2. The methods used and input parameters for computing this profile are contained in Annex A.

The average surge level is 13.5 feet, with bimodal peaks of 15.4 feet and 17.7 feet at central Padre Island and near Orange, respectively. Minimum expected surges of 12.0 feet and 11.5 feet occur at Port Isabel and Rockport, respectively. To these surge heights must be added the initial rise and astronomical tide stage to obtain the total hurricane tide. As explained in Annex A, this increment totals 3 feet to which the freshwater accumulations must be added to compute the total flooding potential.

PROCEDURES FOR COMPUTING INLAND FLOOD LEVELS AND FOR DESIGNATING HAZARD ZONES

The flood levels caused by open coast storm tides, the additional surges which develop over bays and inland water, the tidal maxima at bay shores, and associated inland flooding, are presented in the Annexes to this section.

Annexes A, B, and C present the procedures for computing flood levels and other characteristics which are necessary to identify the hazard zones for a proposed building site in order to select the appropriate model building code.

Annex A contains the background and results of computations of open coast storm tides to be expected from the Texas Design Hurricane.

Annex B describes the methodology and conceptual basis for computing surge maxima at bay shores and the inland flooding these cause.

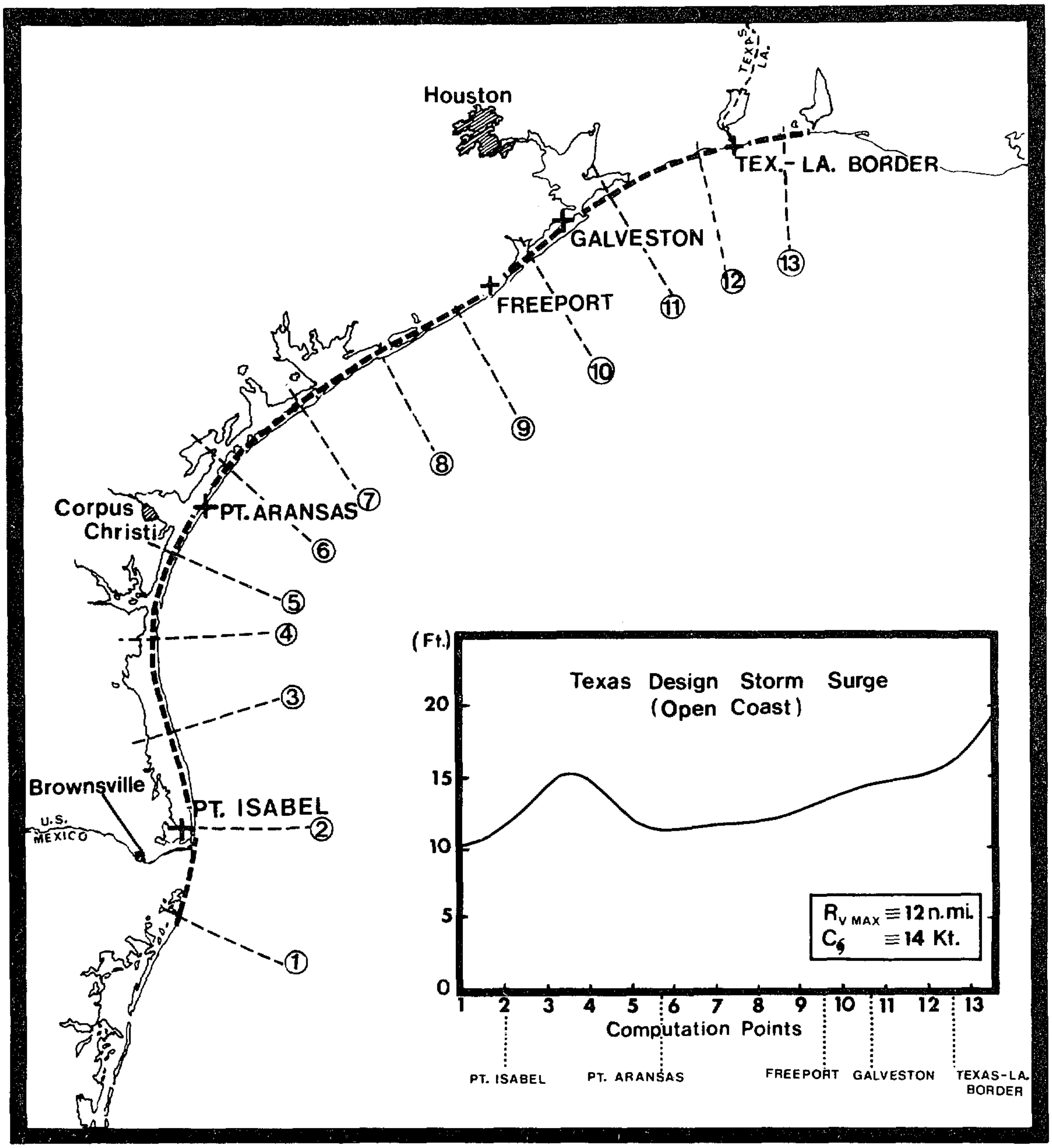

FIGURE III-2

PROFILE OF STORM SURGE AT <u>OPEN</u> COAST

(See A-1 for detailed elevations)

Annex C details the procedures to be used in computing inland flooding profiles and the design flood level at a specific location. Alternative methods for applying these procedures, with sample computations, are presented. They include (1) the use of a nomogram for computing the series of hydrographs needed to construct flood level profiles, and (2) a program for use with a hand-held programmable calculator to accomplish the same purpose more rapidly. A listing of the program for the latter procedure is included. The results using either method are equivalent.

Not presented here, but currently being developed, is a FORTRAN IV program which can be used with almost any modern time-share facility which has a FORTRAN compiler to obtain the same results very quickly.

The time required for determining the design flood level at one location, using the nomogram is nominally 6 hours; with the programmable calculator, 2 hours; and with the FORTRAN program, this can be done with a few minutes of man-time and then only a few seconds of computer-time.

For references, see Appendices following Section IV.

ANNEX A

COMPUTATION OF HURRICANE TIDES AT THE OPEN COAST

The hurricane tide at the open coast is a combination of several components, the principal one of which is storm surge. Other components include (1) the astronomical tide; (2) the "initial rise" or "forerunner tide" (occurring more than 24 hours prior to arrival of the hurricane with range of 1-3 feet); (3) wave setup, (rarely over 2 feet, but in some peculiar bathymetric configurations may be much larger; e.g., Eloise, 1975, where surge may have been only 9 feet, and wave setup 4-6 feet); (4) wave runup (usually small); and (5) rainfall runoff. At two Texas coast locations wave setup may be important: (a) central Padre Island and (b) the Rockport area. Within computational error the open coast hurricane tide on the Texas coast is primarily a function of the computed surge height.

The computations of storm surge profiles for the open coast of Texas have been made for a severe hurricane whose damage potential, in terms of characteristic strength, size, movement, and recurrence frequency, can be effectively and economically mitigated by building design measures.

The climatology upon which the computations were based is taken from a recent study by Ho, Schwerdt, and Goodyear (1975).* The characteristics used in this study, a function of latitude, are listed in Table A-1 and vary up the coast as follows:

1. Central pressure: 903mb at Port Isabel increasing to 937 at Orange.

2. Radius of maximum wind: 14 miles.

3. Hurricane movement at point of landfall: 14 kts.

4. Direction of hurricane approach: normal to the coastline.

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* *NOAA Tech. Report NWS 15 entitled, "Some Climatological Characteristics of Hurricanes and Tropical Storms, Gulf and East Coasts of the United States" (May, 1975).*

TABLE A-1

INPUT DATA FOR SPLASH II PROGRAM TO COMPUTE

SURGE HEIGHTS FOR THE

STATE OF TEXAS DESIGN HURRICANE

Point	Landfall	P_{min} (mb)	δP_{max} (mb)	R_{max} (mi)	C (kt)	Dir. of Storm
1	Pt. Isabel: 30L	903	113	14	14	W
2	Pt. Isabel: 0	904	112	14	14	W
3	Pt. Isabel: 30R	910	106	14	14	W
4	Pt. Isabel: 60R	915	101	14	14	W
5	Pt. Isabel: 90R	920	96	14	14	W
6	Aransas Pass: 12R	925	91	14	14	WNW
7	Matagorda: 6L	928	88	14	14	NW
8	Matagorda: 23R	930	86	14	14	NW
9	Matagorda: 54R	931	85	14	14	NW
10	Galveston: 15L	934	82	14	14	NNW
11	Galveston: 15R	936	80	14	14	NNW
12	Galveston: 45R	937	79	14	14	NNW
13	Cameron, La.: 12L	937	79	14	14	N

This climatology is statistically founded without explicit dynamical constraints and as such may tend to overemphasize the gradient characteristics from southern to northern coastal areas. This may result in a slight underestimate of computed surge heights in the upper coastal reaches. However, the differences are believed to be within the probable errors in distributing the water inland.

The selection of a relatively small radius of maximum wind and fast approach to the coast was adopted as a most equitable compromise in obtaining realistic flood levels at the open coast and for inland reaches of estuaries and bays. A slower-moving storm would provide lower surge values at the open coast and high values for bay shores. A larger radius of maximum wind would be inconsistent with the very low central pressure adopted. The central pressures are those which have an expected return period of 100 years. Realistic values of flooding at bay shores have been built into the procedures for computing inland flooding as a function of wind setup on the inland water bodies described in Annexes B and C.

The model used for computation of the surge profiles, known as SPLASH II, was developed by Jelesnianski (1972). The decision to use this model is supported by the report of a Panel on Coastal Surges appointed by the Building Research Advisory Board of the National Academy of Science.* This report reviews a number of dynamic prediction models and concludes that the Jelesnianski model is the best presently available for computing surges at the open coast.

Computations were made at 13 positions, 30 miles apart for a hurricane approaching normal to the coastline and having the characteristics listed in Table A-1. The results are presented in Figure A-1, where the profile represents the envelope of peak surge values for the 13 computations made. In the procedures for computing the inland flooding, Annex B, the convention adopted is to assume that a preliminary rise of two feet exists both at the coast and on inland water prior to the initiation of rises due to surge. Then an increment of one additional foot due to astronomical tide stage is added to the computed peak storm surge for the Design Hurricane as a basis for deriving the surge hydrograph. This combination is approximately equivalent to the arrival of peak surge at time of spring high tide.

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* *National Academy of Science, Panel of Hurricane Surges, 1975, Washington, D.C.*

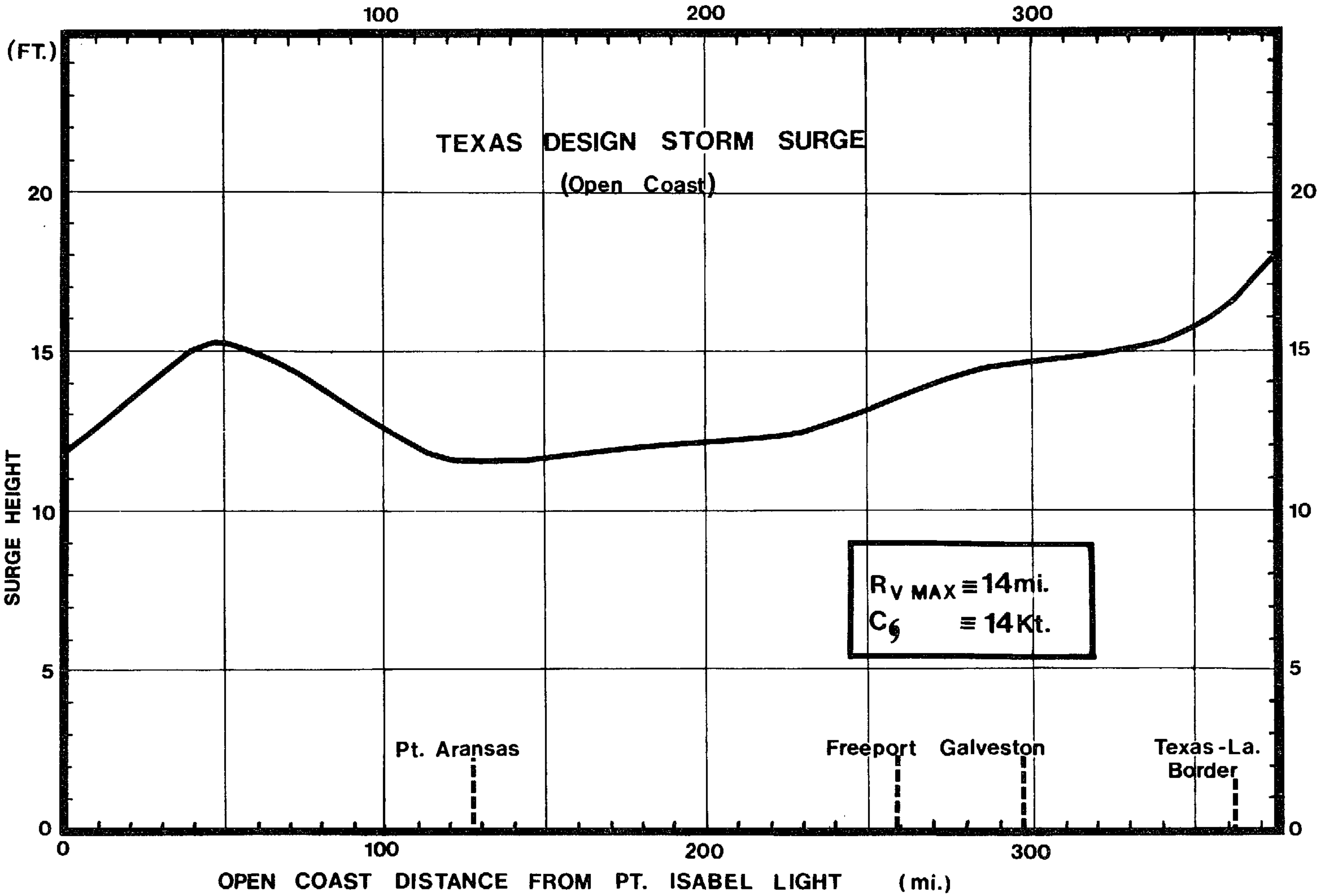

FIGURE A-1

SURGE ELEVATIONS AT <u>OPEN</u> COASTLINE

(Detailed inset from Figure II-2)

HURRICANE HYDROGRAPH

The Design Hurricane characteristics from Table 1 run on the SPLASH II program produce a hydrograph whose shape is essentially that of Figure A-2. Hydrographs were computed for the lower, middle and upper Texas coasts. Since the shape and size is very nearly conserved for constant radius of maximum wind (R) and forward speed (c), a normalization is feasible in which surge values for the design hydrograph are expressed in terms of percentage of peak surge value. Figure A-2, the design hydrograph, shows the rate of rise (and fall) of surge heights at the open coast and is the basis for computing the distribution of surges inland. It should be noted that the rate of fall implied is not real, however, since the retreat of inundation is more complex than the advance and involves in many uses additional water volume accumulations (rain and riverine discharges) and much larger bottom or frictional stresses. Therefore, the ebb rate will be distorted, usually (but not always) being slower than the computed rate. Figure A-3 is a schematic showing spatial distribution along the coast and vertical rise prior to landfall.

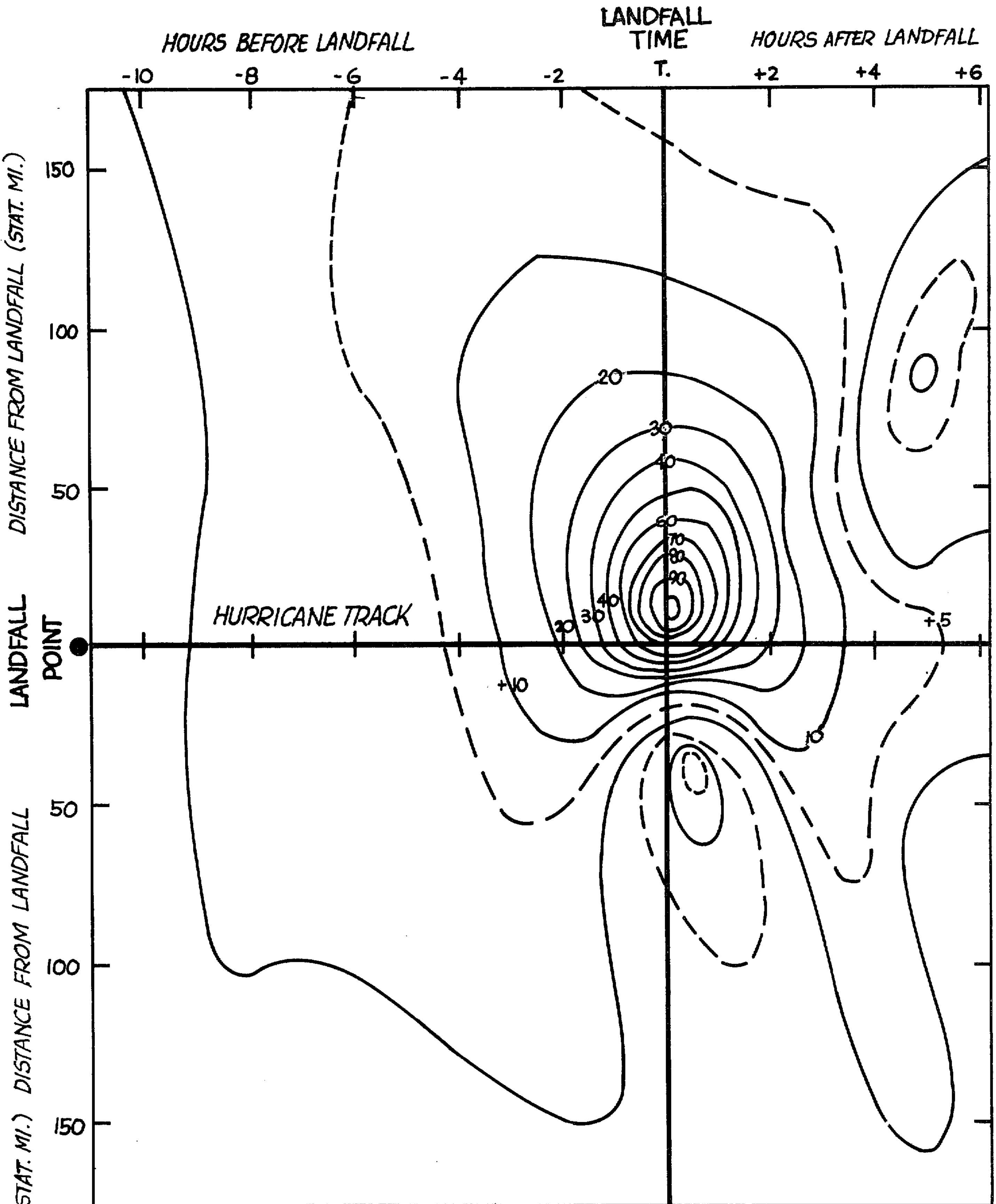

FIGURE A.2

TIME HISTORY OF OPEN COAST STORM SURGE HEIGHTS FOR DESIGN HURRICANE. (THIS IS A NORMALIZED HYDROGRAPH SURFACE EXPRESSED IN TERMS OF PERCENTAGES PEAK SURGE ENVELOPE GIVEN IN FIGURE A.1)

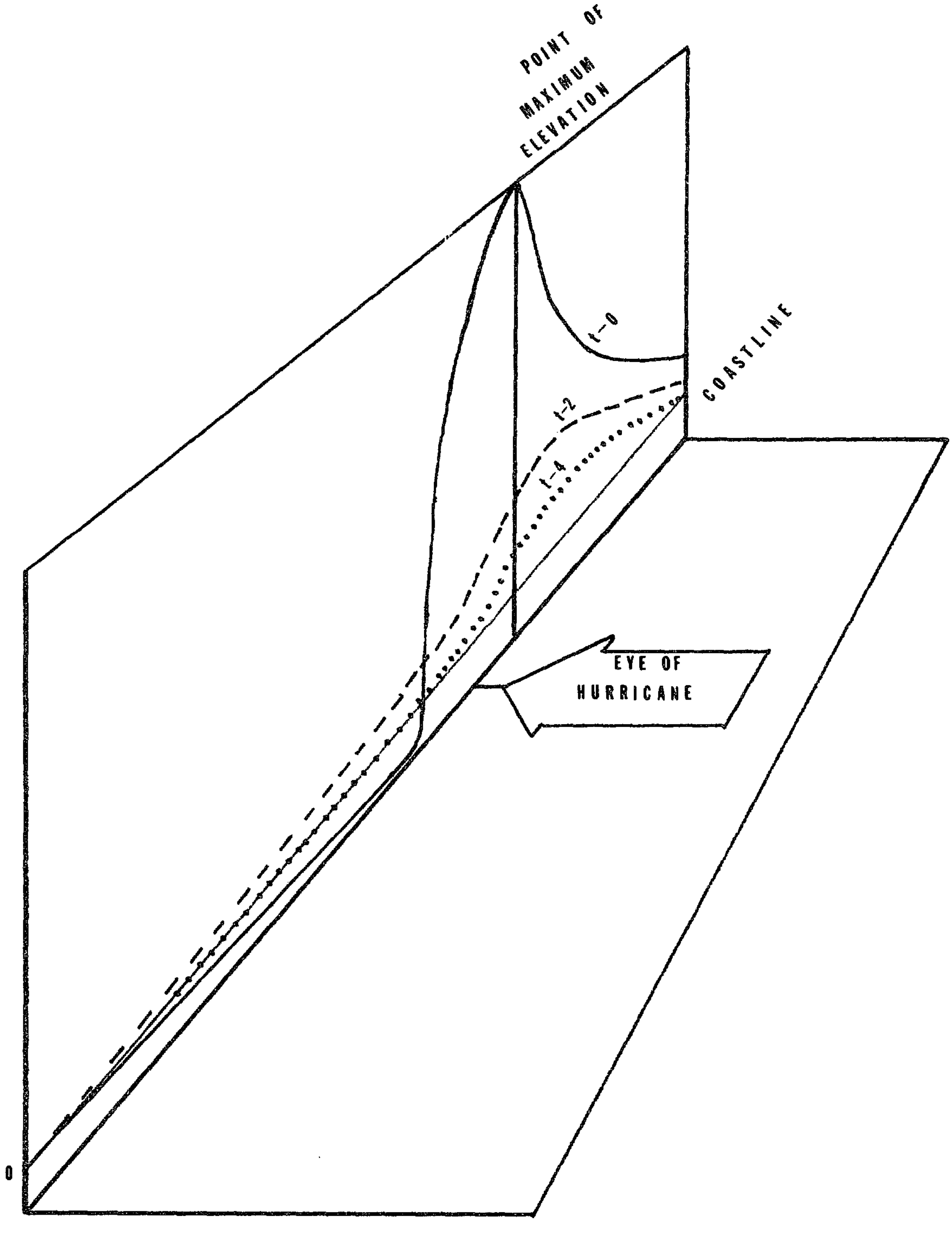

FIGURE A-3

SCHEMATIC SHOWING RISE OF SURGE ALONG OPEN COASTLINE BEFORE LANDFALL AND SPATIAL DISTRIBUTION ALONG COAST.

ANNEX B

CONCEPTUAL BASIS FOR COMPUTING INLAND FLOODING

The Texas coast comprises mainly a chain of barrier islands separated from the mainland by narrow shallow bays or lagoons, a few of which expand into larger, deeper bays or estuaries as in the Corpus Christi, Galveston and Matagorda areas. Tides from severe hurricanes will overtop portions, if not all, of most barrier islands, combining with the wind-driven shoal waters of bays and estuaries to flood the lee shores. The routing of these floodwaters is accomplished by using a procedure designed by the Institute for Storm Research at Houston, Texas. This procedure requires as input:

1. a hydrograph or chronology of the storm tide stages at the open coast for the period 10 hours before through 6 hours after hurricane landfall (see Figure A-2);

2. the hurricane wind field corresponding to the hydrograph values for the line of computation. This line, which is parallel to and 14 miles to the right of the hurricane track, passes through the position of tidal maximum at the open coast (see Figures B-1a and B-1b).

3. a topographic profile of ground (or bottom) levels, relative to mean sea level, extending inland normal to the open coast or bay shore (whichever is applicable) through the point (Q) for which the hazard zone is to be determined.

The initialization selects the appropriate design surge maximum for the coastal point in question (Figure A-1). Hydrograph computations to complete Table B-1 are made in terms of a peak tidal value comprising the peak surge plus an astronomical tide of one foot MSL (2.1 feet MLW), considered to arrive at the coast or shoreline coincident with the surge maximum. To the computed hydrograph from Table B-1 is added an invariant value of initial rise, 2.0 feet, to obtain the total tidal stage for each time step in the computation of inland flooding.

For flood routings across land, or over inland water surfaces less than 5.5 feet deep (MSL), the line of computation is positioned to pass through (Q) and to cross the open coast (P) at right angles (see Figure B-2).

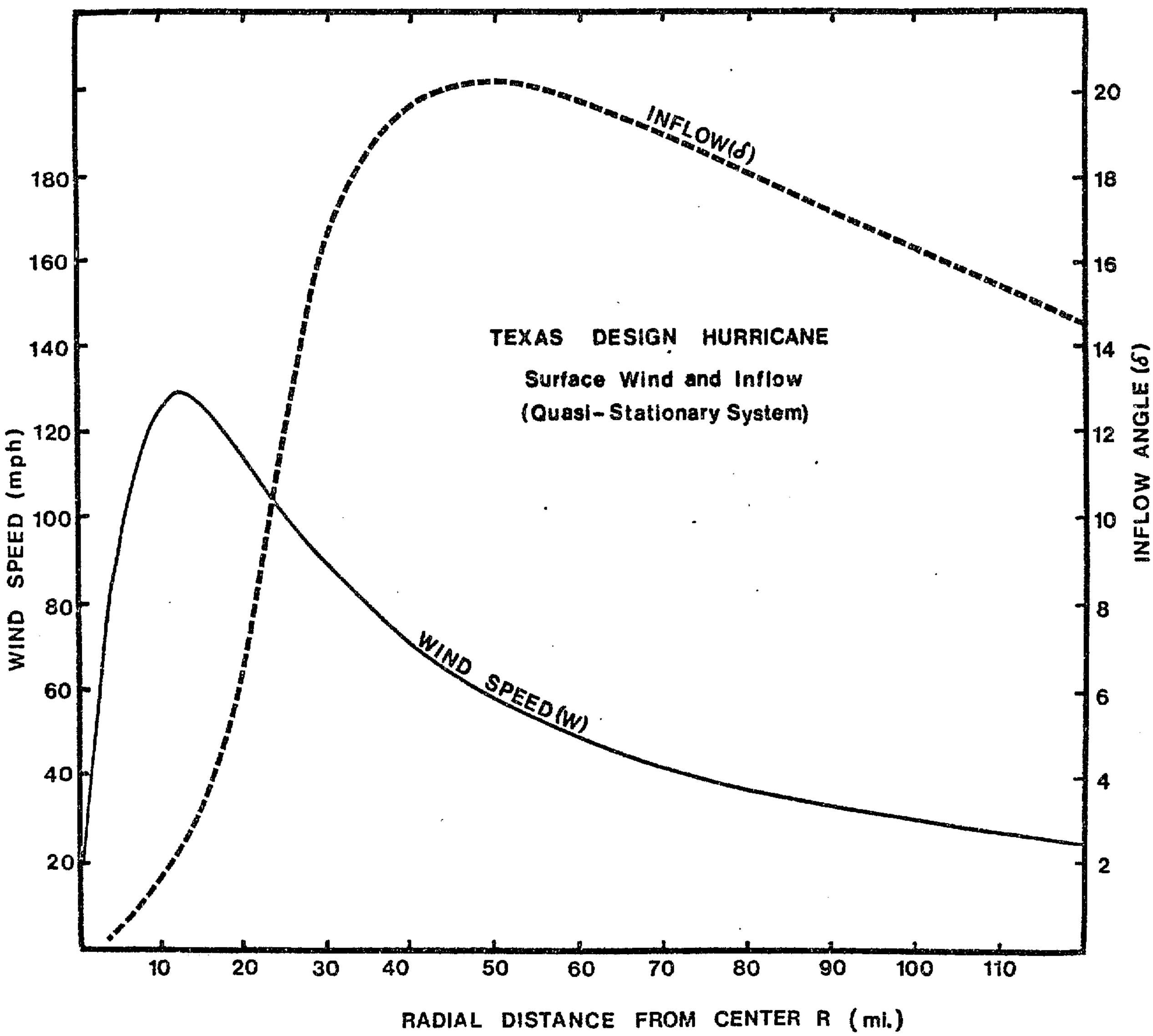

FIGURE B-1A

COMPOSITE WIND FIELD FOR THE TEXAS DESIGN HURRICANE FOR A <u>QUASI-STATIONARY SYSTEM</u> BASED UPON SPLASH II COMPUTATIONS.

The actual wind field (Figure B-1b) accounts for the hurricane movement by addition of a component of movement $n\underline{C}$, where $\underline{C}$ is the vector of movement (down track) and n is an empirical coefficient in the SPLASH model.

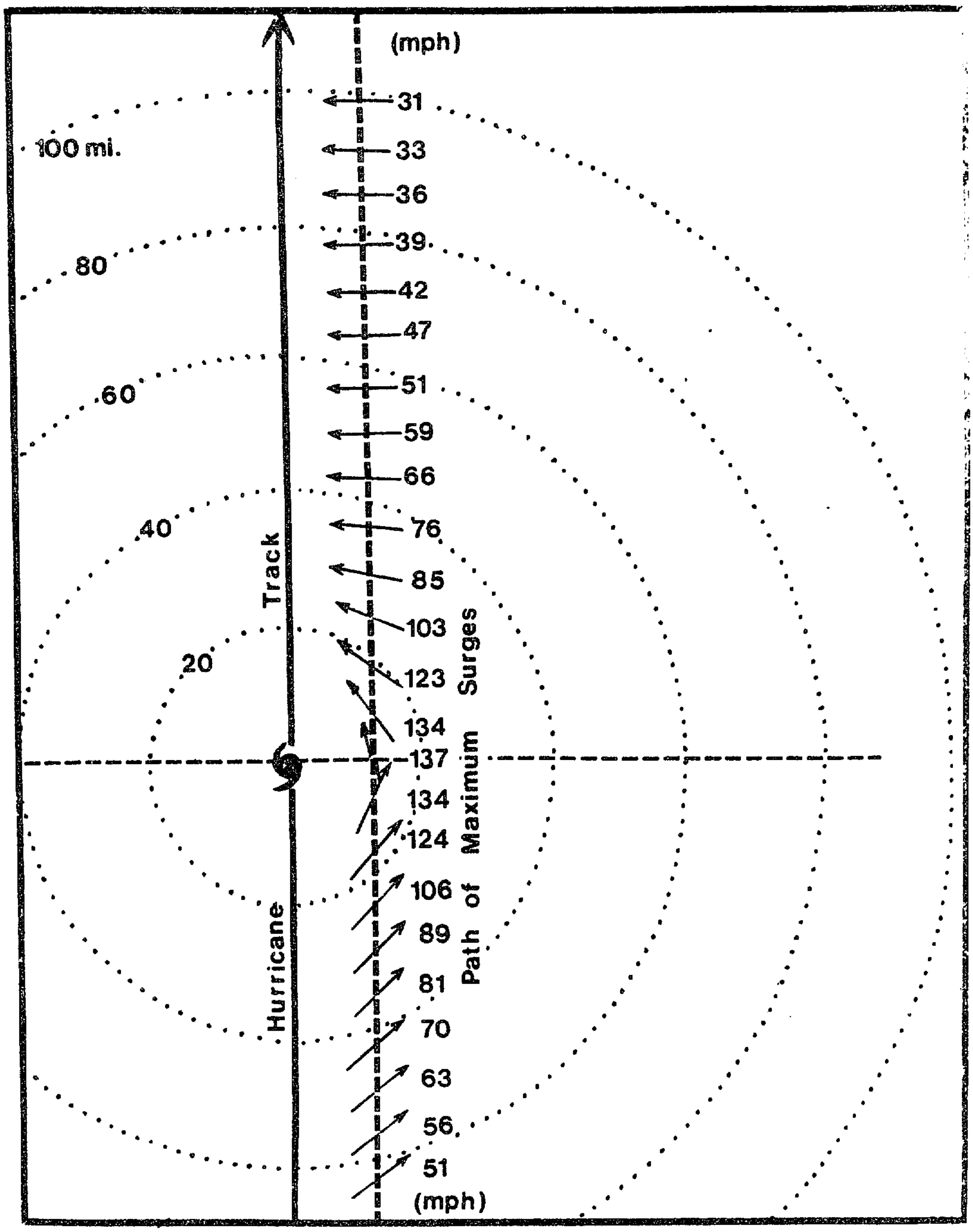

FIGURE B-1B

COMPOSITE WIND FIELD FOR THE LINE OF COMPUTATION USED IN THE TEXAS DESIGN HURRICANE MOVING INLAND AT 14 KNOTS.

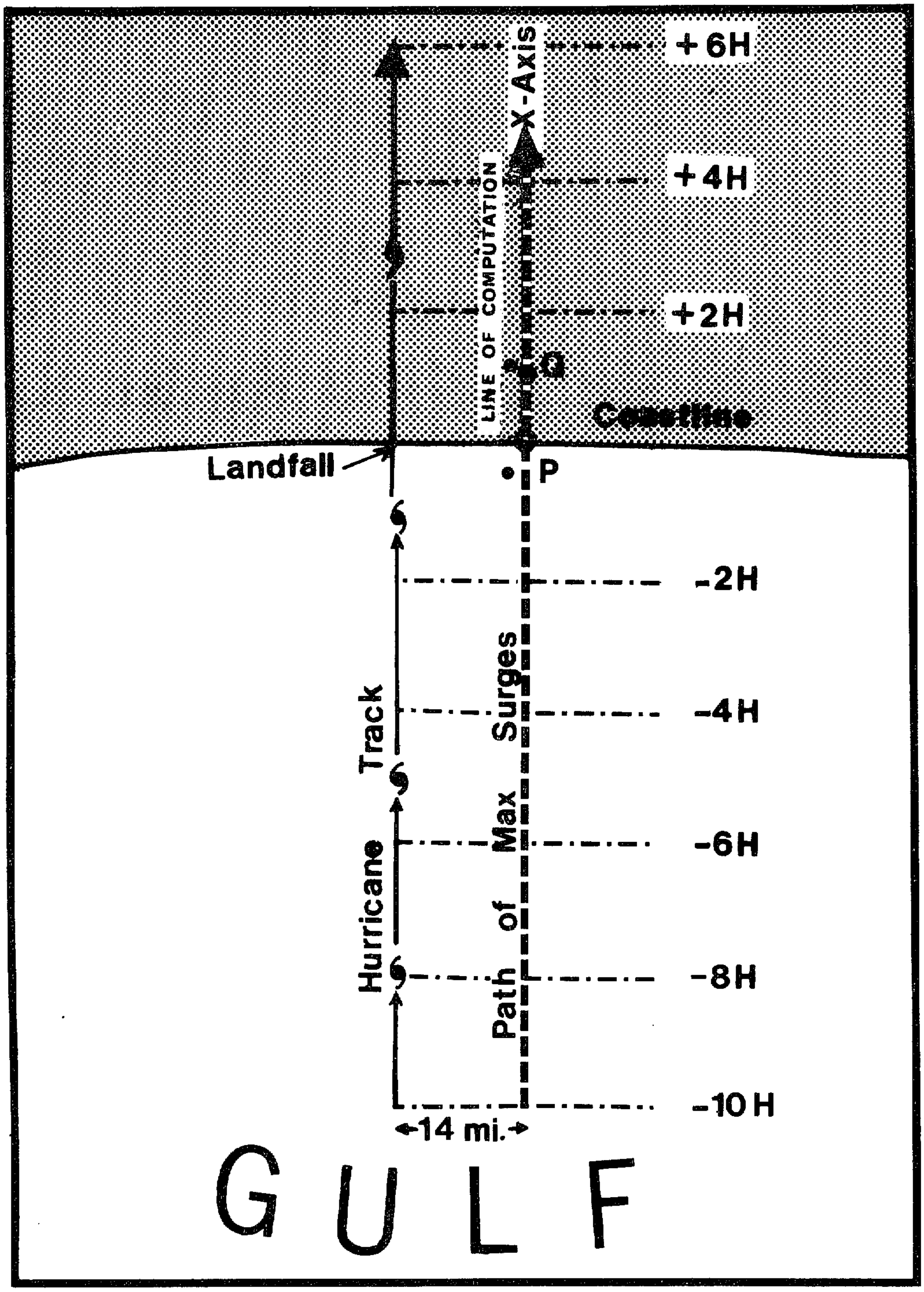

FIGURE B-2

ORIENTATION OF LINE OF COMPUTATION FOR DISTRIBUTING OPEN COAST HURRICANE TIDES INLAND AND OVER SHOAL INLAND WATERWAYS

For flood routings across bays or estuaries of greater depth, the tilting up of the water surfaces at lee shore due to wind setup may bring even larger inundations than at the open coast if severe hurricane winds operate on the water surface for 90 minutes or more. (In Carla inland flooding reached the 22 foot level, while tidal maxima at the coast were only about 15 feet.) Therefore, a special computation procedure is used for determining the surge maximum due to wind setupt. This surge maximum, physically determined, is a function of the water depth (MSL) and an optimal distance over which hurricane winds can operate on the shallow water basin. Procedures for these computations are contained in Annex C. A sample computation sheet is shown in Figure B-3.

The computation procedure uses a chart similar to that in figure A-2. This is an x-t diagram where the x-axis is the line of computation directed landward. The t-axis extends from -10 hours (before landfall) to +6 hours. The initial input is based upon the expected peak surge value selected from Figure A-1, the computed hydrograph for the open coast (x=0, t=-10 to +6) from Table B-1, and the wind history accompanying the hydrograph (Table B-2). Hydrograph points (for -10 H to +6H) are computed at 7.5, 15, or 30-minute intervals depending upon the length of spatial steps on the x-axis. The spatial computation intervals used are a function of the distance inland of point Q and range from 1 to 4 miles.

ROUTING OF RAINFALL RUNOFF

The design hurricane expects a rainfall of 8 inches uniformly distributed over a semicircular area 28 miles in diameter extending landward from point P and occurring at a uniform rate during the 4-hour period prior to the arrival of the peak storm tide at point Q.

It is assumed that initially river and stream levels are normal, that prior to the beginning of heavy rains (4 hours before the hydrograph peak is reached), the rainfall saturates and is largely absorbed by the soil, and that normal drainage systems are functional. During the last 4 hours, the rapid hydrograph rise due to saltwater intrusions blocks the urban and natural drainage systems for fresh water accumulating at point Q.

For purposes of this computation, the contributions of riverine flooding over the short period of hurricane approach are considered small and thus incorporated in the value of the initial rise. The rainfall runoff cannot be dismissed

TABLE B-1

TEXAS DESIGN HURRICANE

The wind field lies along a line parallel to the track and passing through the tidal maximum, from 10 hours before until 6 hours after landfall. If this line is defined as the x-axis increasing downtrack, θ is the angle which a wind vector observed on this line makes with the line, positive when measured counterclockwise from the x-axis. (Based upon hydrograph and computed winds from SPLASH II program [Jelesnianski, 1972], using TEXAS DESIGN HURRICANE parameters.)

LANDFALL		SURFACE WIND		OPEN COAST TIDE	
Distance D(mi)	Time (Hours)	Speed W(mph)	Track Crossing Angle θ (deg)	Fraction of Max	Hurricane Tide N(MSL)
-140	-10.0	22	80.1	.00	
-133	- 9.5	23	81.0	.005	
-126	- 9.0	24	81.9	.01	
-119	- 8.5	25	82.7	.015	
-112	- 8.0	27	84.3	.02	
-105	- 7.5	29	85.5	.023	
- 98	- 7.0	31	86.5	.025	
- 91	- 6.5	33	87.3	.027	
- 84	- 6.0	36	88.4	.030	
- 77	- 5.5	39	89.2	.040	
- 70	- 5.0	42	89.7	.05	
- 63	- 4.5	47	90.1	.075	
- 56	- 4.0	51	90.5	.10	
- 49	- 3.5	59	89.7	.16	
- 42	- 3.0	66	88.2	.22	
- 35	- 2.5	76	85.1	.26	
- 28	- 2.0	85	79.1	.30	
- 21	- 1.5	103	68.0	.45	
- 14	- 1.0	123	50.2	.60	
- 7	- .5	134	31.6	.85	
0	0.0	137	2.2	1.00	
7	0.5	134	-26.0	.85	
14	1.0	124	-43.7	.60	
21	1.5	106	-46.0	.40	
28	2.0	89	-46.3	.20	
35	2.5	81	-47.9	.12	
42	3.0	70	-49.3	.05	
49	3.5	63	-50.6	.025	
56	4.0	56	-51.6	.00	
63	4.5	51	-52.9	- .05	
70	5.0	46	-53.6	- .10	
77	5.5	43	-55.2	- .07	
84	6.0	40	-54.8	- .03	

TABLE B-2
WIND HISTORY FOR TEXAS DESIGN HURRICANE
Based upon SPLASH II Stationary System Wind Field Corrected for Design Hurricane Movement.

QUASI-STATIONARY SYSTEM									MOVING SYSTEM	
R (mi)	W (Kt)	δ (deg)	D (mi)	t (hours)	θ'_{tan} -(deg)	δ' (deg)	θ'_s ($\theta'_{tan} + \delta'$)	W'_s Kt	θ (deg)	W (Kt)
4	78	0.44	-140	-10.0	85.1	13.3	98.4	22	80.1	22
8	119	1.18	-133	- 9.5	84.8	13.7	98.5	23	81.0	23
12	130	2.27	-126	- 9.0	84.6	14.2	98.7	24	81.9	24
16	124	4.04	-119	- 8.5	84.2	14.7	98.9	25	82.7	25
20	114	6.67	-112	- 8.0	83.9	15.3	99.2	27	84.3	27
24	103	11.21	-105	- 7.5	83.5	15.9	99.4	29	85.5	29
28	94	15.32	- 98	- 7.0	83.0	16.5	99.5	31	86.5	31
32	85	17.77	- 91	- 6.5	82.5	17.0	99.5	33	87.3	33
36	78	19.14	- 84	- 6.0	81.9	17.7	99.6	36	88.4	36
40	71	19.88	- 77	- 5.5	81.1	18.4	99.5	39	89.2	39
44	66	20.24	- 70	- 5.0	80.3	19.0	99.3	42	89.7	42
48	61	20.34	- 63	- 4.5	79.2	19.5	98.7	47	90.1	47
52	57	20.28	- 56	- 4.0	77.9	20.3	98.2	52	90.5	51
56	53	20.10	- 49	- 3.5	76.2	20.3	96.5	59	89.7	59
60	50	19.87	- 42	- 3.0	74.1	20.2	94.3	66	88.2	66
64	47	19.57	- 35	- 2.5	71.1	19.3	90.4	76	85.1	76
68	44	19.22	- 28	- 2.0	66.8	17.0	83.8	84	79.1	85
72	42	18.86	- 21	- 1.5	60.5	11.4	71.7	101	68.0	103
76	40	18.46	- 14	- 1.0	49.4	3.4	52.8	119	50.2	123
80	38	18.11	- 7	- 0.5	30.3	2.9	33.2	128	31.6	134
84	36	17.81	0	0	0	2.3	2.3	130	2.2	137
88	35	17.43	7	0.5	-30.3	2.9	-27.4	128	-26.0	134
92	33	17.07	14	1.0	-49.4	3.4	-46.0	119	-43.7	124
96	32	16.71	21	1.5	-60.3	11.4	-48.9	101	-46.0	106
100	31	16.36	28	2.0	-66.8	17.0	-49.8	84	-46.3	89
110	28	15.51	35	2.5	-71.1	19.3	-51.8	76	-47.9	81
120	25	14.73	42	3.0	-74.1	20.2	-53.9	66	-49.3	70
130	23	14.00	49	3.5	-76.2	20.3	-55.9	59	-50.6	63
140	22	13.32	56	4.0	-77.9	20.3	-57.6	52	-51.6	56
150	21	12.83	63	4.5	-79.2	19.5	-59.7	47	-52.9	51
			70	5.0	-80.3	19.0	-61.3	42	-53.6	46
			77	5.5	-61.1	18.5	-63.6	39	-55.2	43
			84	6.0	-31.9	18.0	-63.9	36	-54.8	40

Hurricane Tidal Inundation
Computation Sheet

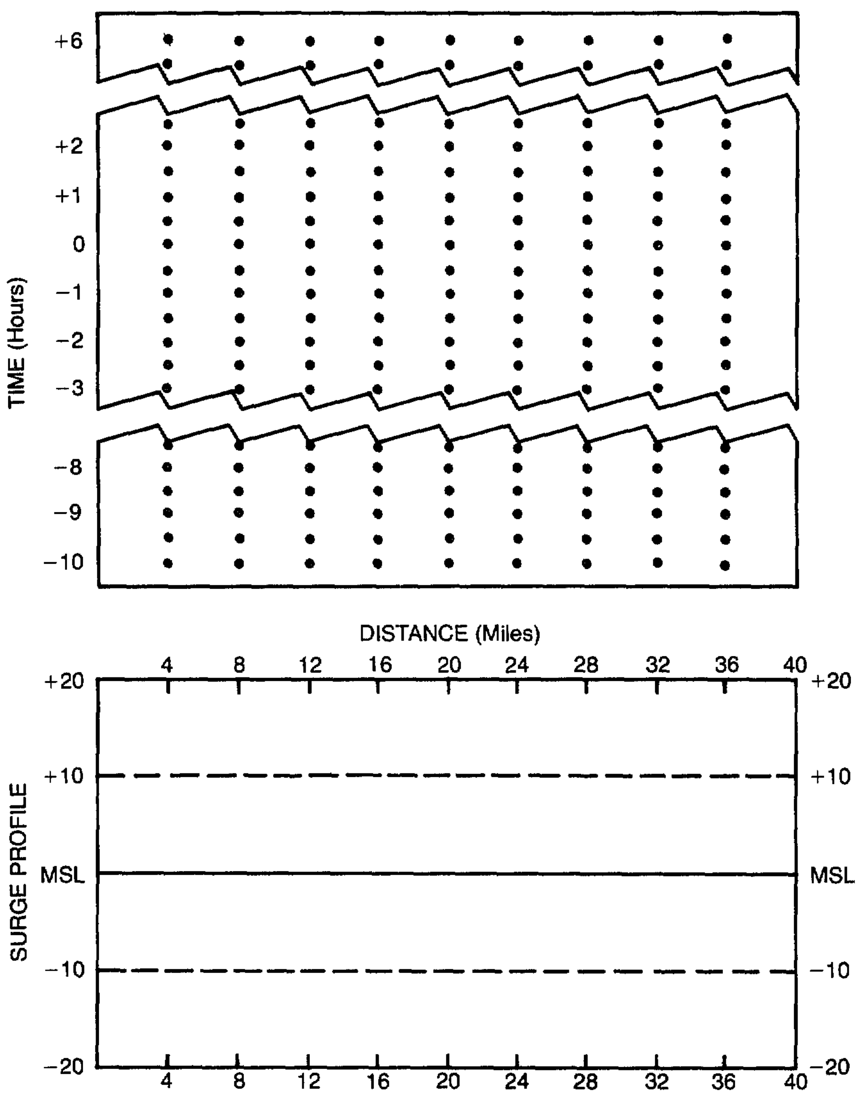

FIGURE B-3

BASIC COMPUTATION SHEET AND VERTICAL SECTION FOR CONSTRUCTING PROFILES OF MAXIMUM FLOOD HEIGHTS INLAND FROM THE OPEN COAST so easily, however. While this contribution is acknowledged as likely to vary appreciably with topography, for purposes of this computation the freshwater contribution is considered to be 0.7 feet. This value is added directly to the maximum saltwater depth computed for point Q to determine total flooding levels.

ANNEX C

PROCEDURES FOR COMPUTING INLAND FLOODING

Annex B explains the conceptual basis for computing the inland flooding due to storm surges. This annex sets forth the procedures which, if followed closely, will provide the computational results which are fundamental to the effectiveness of this program. These procedures draw upon many different sources of competence to compute flooding levels and identify in which hazard zone a proposed building site is located. The final determination of the hazard zone must combine the maximum computed flooding level at the building site (Q) with the prima facie factors identifying the hazard zones specified on pages III-5 through III-8.

1. FORMULATION SUMMARY. The procedure for routing storm tidewaters inland computes the flux from the equation for steady-state flow. This includes the forces due to (1) wind stress on the water surface, (2) gravity action due to the mean slope of the water surface, and (3) bottom stresses given by Mannings formula. A hydrograph is computed for successive space steps, x_1 to x_n, along an x-axis extending inland from the point of maximum storm tide at the beach or shore (P), passing through Q, the site in questions. The procedure solves the equation

$$N_A = N_B + K_3\,[P(C,R) - P(L,C)] \qquad (1)$$

where the tidal flux for a given time step is $N_A - N_B$. This computation derives from the function

$$P(l,r) = \sqrt{K_1(h'-hg)^{10/3}(N_r-N_l) + K_2W^2\cos\theta(h'-hg)^{7/3}} \qquad (2)$$

expressed relative to the grid array

$$\begin{array}{cc} N_l & N_r \\ \bullet & \bullet \\ hg_l & hg_r \end{array}$$

The total water depth $(h' - hg) = \left(\frac{N_r - hg_r}{2} + \frac{N_l - hg_l}{2}\right)$

Symbols and constants are defined on page III-C-16.

In (2) if the quantity under the radical is defined as B, the convention is that $P(l,r) = \sqrt{B}$ if B is positive
$= -\sqrt{-B}$ if B is negative

To simplify computations, it is assumed that all terrain is initially covered by 0.2' of water, so that for all time periods before surge waters have extended inland to a position x_i, for which a hydrograph is being computed, the value of N (water level above MSL) is 0.2' greater than hg (terrain level MSL).

The maximum storm tide at x_i is obtained from the computed hydrograph for x_i and plotted on a vertical cross section of N_{max} vs. x to obtain the profile and inland extent of saltwater flooding. To the water depth at Q obtained from this profile is added the accumulation of fresh water from rain runoff, nominally 9.7 ft., to obtain the computed depth of flooding at Q. Finally, the design depth at Q is considered to be the computed depth if greater than that which would exist in terms of the floodplain level established by FIA. If lower, the design depth will be equal to that defined by the floodplain.

2. CLASSIFICATION AND INITIALIZATION.

2.1 Locate the building site Q on a coastal map. Select a map preferably with a scale of 1" = 2000 ft., but not smaller than 1" = 1 mile. Contours of elevation (and for inland waters the bottom depths) should have a resolution of not less than 5 feet.

2.11 Draw a line through Q normal to the bay shore or coastline terminating at point P, the water's edge at MSL.

2.12 Measure the distance S from point P to point Q in tenths of miles, and the elevation H' (MSL) for point Q.

2.2 Select the appropriate space and time increment (Δx, Δt) for making computations.

2.21 If S is 12 (statute) miles or more, use the following increments: Δx = 4 miles; Δt = 30 min.

2.22 If S is greater than 6 miles, but less than 12: Δx = 2 miles; Δt = 15 min.

2.23 If S is 6 miles or less: Δx = 1 mile; Δt = 7 1/2 min.

2.3 Construct and label an appropriate computation sheet following the example in Figure B-3.

2.31 If P is located at a narrow barrier ridge or continuous line of dunes, the computation will begin with the time step at which the surge height N is just below the mean height of the ridge. Conceptually, the ridge is regarded as a sill over which surge waters upon reaching that height cross freely and quickly. For other circumstances the procedures in 2.32-2.34 apply.

2.32 If Δx = 4 miles the computation will nominally be conducted for x = 0 to $n\Delta x$, where n is the integer $(S/\Delta x) + 1$, and from t = -10 to +6 hours (unless started later due to terrain conditions in 2.321).

2.321 If terrain rises rapidly at the shore to a height of $hg \geq 6$ ft. MSL, the computations will begin at the hydrograph hour most nearly corresponding to a tidal stage equal to $hg_0 - 0.5'$, where hg_0 is the mean height of terrain immediately adjacent to the shoreline.

2.33 If Δx = 2 miles, the computation will be conducted for the time interval:

-5 to +3 hours,
or t(hg) to +3 hours

whichever is shortest. Here t(hg) is the time the hydrograph at P reaches the height $N(t) = hg_0 - 0.5'$.

2.34 If Δx = 1 mile, the computation will be conducted for the time interval:

-3 to +1.5 hours,
or t(hg) to +1.5 hours

whichever is shorter. t(hg) is the time the hydrograph at P reaches a height of $hg_0 - 0.5'$.

2.35 When a computation begins at a new time step the <u>value of N</u> for x_1 to x_n <u>should</u>

BAY SHORE INUNDATION

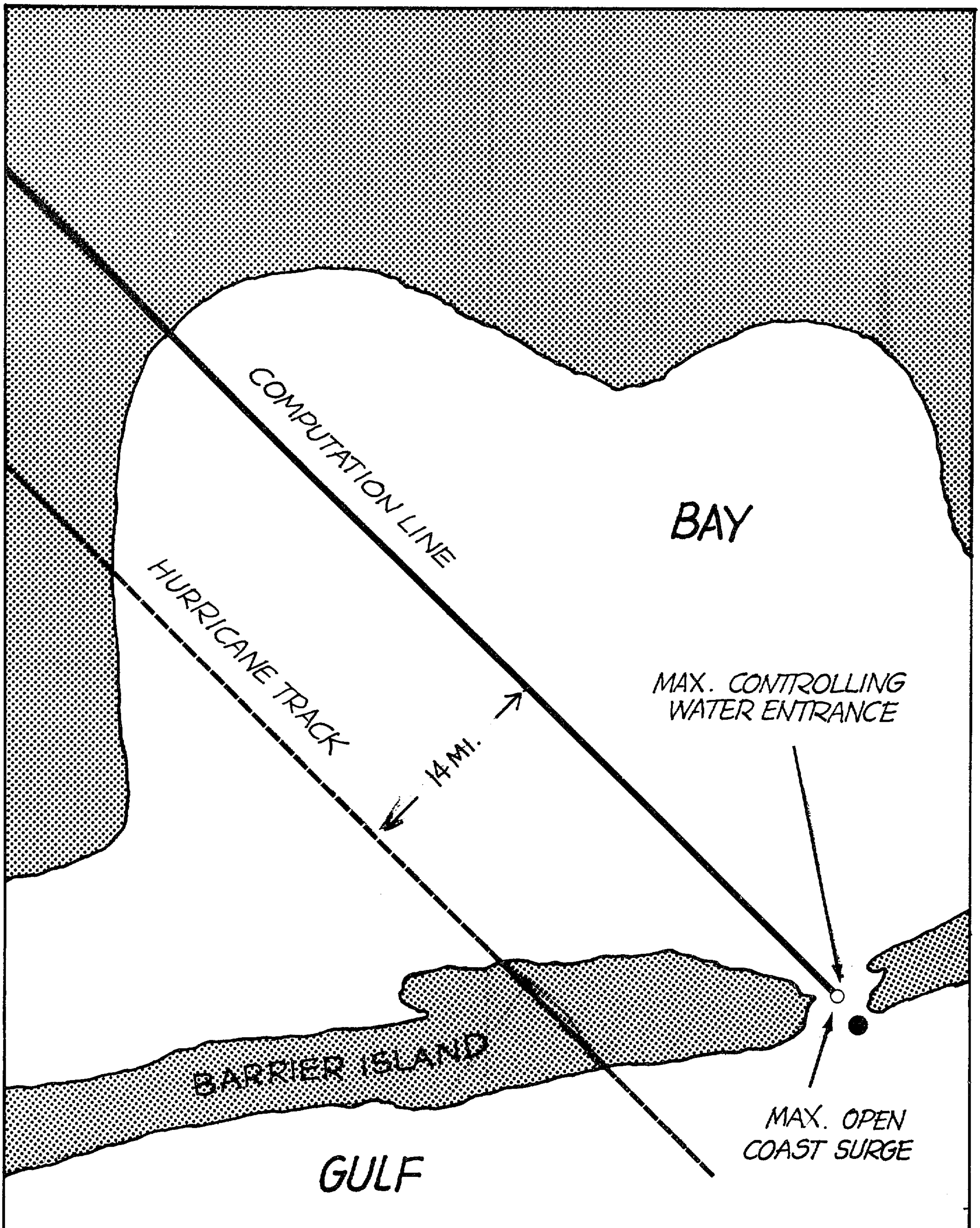

FIGURE C-1

ORIENTATION OF LINE OF COMPUTATION FOR ROUTING COASTAL SURGES INLAND ACROSS LARGER BAYS, AND FOR COMPUTING BAY SHORE INUNDATIONS.

not be less than

(a) hg + 0.2', or

(b) 2 ft., MSL, or

(c) half the value of N at x = 0 whichever is largest.

2.4 From Table B-2 record the appropriate values of θ and W to the left of each time step on the computation chart, Figure B-3.

2.5 Compute the hydrograph for x_o. If P is at an inland shore where mean water depths across the bay are at least 5.5 feet MSL, proceed to 2.53; if P is at the open coast, proceed as follows:

2.51 From figure A-1 determine the maximum surge height (feet and tenths) for the Texas Design Hurricane at the coastline position nearest to P.

2.52 To this surge height add 1.0 feet (astronomical tide increment). Using the sum as the peak open coast tide (MSL) compute the hydrograph values for each time step in Table B-1. Proceed to step 2.54.

2.53 Compute the equilibrium tilt of the water surface in the bay (see Figure B-2).

2.531 Select a point at the open coast, 0, which (1) maximizes the distance OP (this line need not be normal to the coastline), and (2) is centered in a major pass connecting the ocean with the inland waters, or alternatively is centered on an 8-mile stretch of coast where the barrier island, dunes or stable terrain, offers the lowest mean elevation to block movement of the open coast surge.

2.532 Compute the equilibrium height of water surface N_x at point P as a function of distance S' from 0 to P and of mean water depth (below MSL) H.

Use the formula $N_x(\text{ft.}) = \dfrac{10.58S'}{H + h} + T$

where h is the initial rise ≡ 2 ft. MSL and T, the astronomical tide ≡ 1.0 ft. MSL. H is taken as the mean depth MSL for a strip 2 miles wide extending from 0 to P. N_x is the peak storm tide at P.

2.533 Enter Table B-1 with the peak tide value, N_x; compute the hydrograph values for each time step. To this add the initial rise 2.0 ft. and enter the sum N(t) on the computation sheet. Proceed to step 2.6.

2.54 Add the height of <u>initial rise</u> (2.0 feet) to the hydrograph values computed in 2.52 and record the sum at each respective time step for x = 0 on the computation sheet.

2.6 Compute hg and N for each space step x_i.

2.61 From the map contours (2.1) plot a profile of terrain heights (or shoal water depths) from P inland to a point at least one space step beyond point Q where hg must be more than 1 ft. above N at the previous space step; or for very flat, low terrain, at least 8 miles beyond Q.

hg should be representative values for the area, nominally the mean hg's whose width extends one half mile to either side of the x-axis.

2.62 On the computation sheet at the initial time step, record the value of hg for each x_i.

2.63 Above each hg value record the value of N, where N ≡ hg + 0.2' except where hg + 0.2' is less than the initial rise (2.0' MSL). In the latter case N ≡ 0.2'.

3. COMPUTATIONS OF HYDROGRAPHS FOR SUCCESSIVE SPACE STEPS INLAND. The computation sheet, similar to figure B-3, now has appropriate initial values of W, θ, and N for x = 0 (point P) at each time step, and values of hg, and for N at the initial time step for each space step, x_1 to x_n. The next step is to compute hydrograph values of N for each time step at x_1, x_2----x_n. Each

computation uses the graphic convention below:

$$
\begin{array}{lccc}
 & & N_A & \\
 & & \bullet & \\
 & N_L & N_C & N_R \\
[t_j,\ (W,\theta)_j] & \bullet & \bullet & \bullet \\
 & hg_L & hg_C & hg_R \\
 & & \bullet & \\
 & & N_B & \\
 & & (x_i) &
\end{array}
$$

3.1 <u>Convention for computing N_A from baseline data.</u> The initial computation, made at $(t_o,\ x_1)$ uses values of N_L, hg_L, N_C, hg_C, N_R, hg_R already recorded in the initialization. For this baseline computation N_B is set equal to N_C. Accordingly, the resulting value of N'_A must be adjusted so the recorded value is:

$$N_A = \frac{(N_C + N'_A)}{2}$$

3.2 <u>Convention for computing successive N_A's for a given time period</u>. After computing N_A for position x_1, move to the right (inland) computing successive N_A's for the same time period, N_R for the first computation becoming N_C for the second. When a space step is reached where <u>hg_R is more than a foot higher than N_C</u>, then for the space step corresponding to this hg_R set $N_A = N_C$ and proceed to the next time step.

3.3 <u>Compute N_A using the HP-65 programmable calculator</u>.

3.31 With the calculator "on" in the "RUN" position, insert the program chip for the appropriate space step: 1-, 2-, or 4- miles.

3.32 Key in the value of θ; STRIKE C. Key in the value of W; STRIKE R/S.

3.33 Key in N_L and store in 2;

Key in hg_L and store in 3;

Key in N_C and store in 4;

Key in hg_C and store in 5.

3.34 STRIKE A.

3.35 If hg_R is more than one foot greater than N_C, STRIKE D, then STRIKE B. Proceed to 3.37. (This is considered by the program as a "cliff effect" and sets $P(R) \equiv 0$.) However, if $(hg_R - N_C) \leq 1.0'$, then

3.36 Key in N_R and store in 4;

Key in hg_R and store in 5.

STRIKE A (let it finish computing!)

STRIKE B

3.37 Key in N_B

STRIKE R/S

The displayed value is N_A.

3.38 Compute the next N_A to the right (inland).

3.381 Let N_R and hg_R in 3.36 become N_C and hg_C, then moving to the right for a new N_R and hg_R:

3.382 Key in N_R and store in 4;

Key in hg_R and store in 5.

STRIKE A (see 3.35 for exception)

STRIKE B

3.383 Key in N_B.

STRIKE R/S

The value displayed is the new N_A.

3.384 Continue to the right until $(hg_R - N_C) > 1.0$ ft., then set $N_A = N_C$.

3.39 Go to the next time step, key in new values of θ and W, and proceed as in 3.32 and 3.33.

3.391 <u>In order to maintain computational stability:</u>

3.3911 For time steps following t = 0, when (N_C - N_A) becomes greater than 1 ft., then for all succeeding time steps the convention requires that $N_A \leq N_C$.

3.4 <u>Compute the profile of saltwater flooding inland</u>.

3.41 Identify the highest value of N computed for each space step inland. This will come at <u>positive</u> time values (following t = 0) and at successively later hours for each succeeding space step.

3.42 Plot values of N_{max} for each space step on the N/x cross section at the bottom of the computation sheet (see Figure B-3) and draw the flood profile.

3.43 From the profile read the inundation depth at Q due to saltwater inundation.

3.44 To the above value add the design value of freshwater flooding, 0.7 ft. to obtain the <u>total flood level D for point Q.</u>

3.45 Determine the legal floodplain height established by the Flood Insurance Administration (HUD) for Q.

3.451 The flooding at Q due to F is defined as $D' = F - hg_Q$. If $D' > D$, set $D = D'$.

3.452 $D \equiv$ design flooding at Q.

3.5 <u>Compute N_A using the ISR nomogram</u> (figures C-2 and C-3).

3.51 Using the lower portion of the nomogram, locate the intersection of the horizontal line for θ values and the vertical line for W; designate this A.

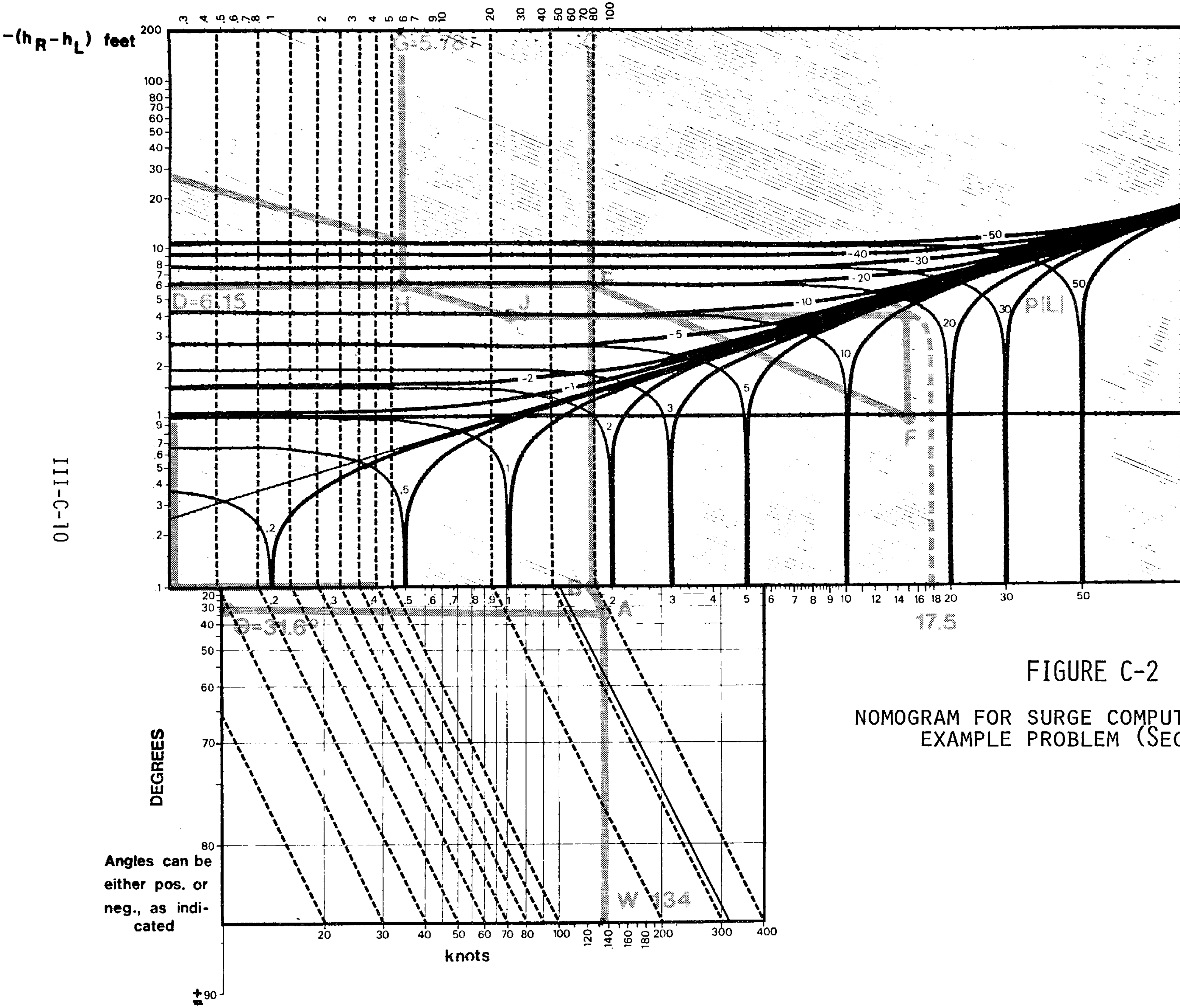

FIGURE C-2

NOMOGRAM FOR SURGE COMPUTATIONS
EXAMPLE PROBLEM (Sec. 3.5)

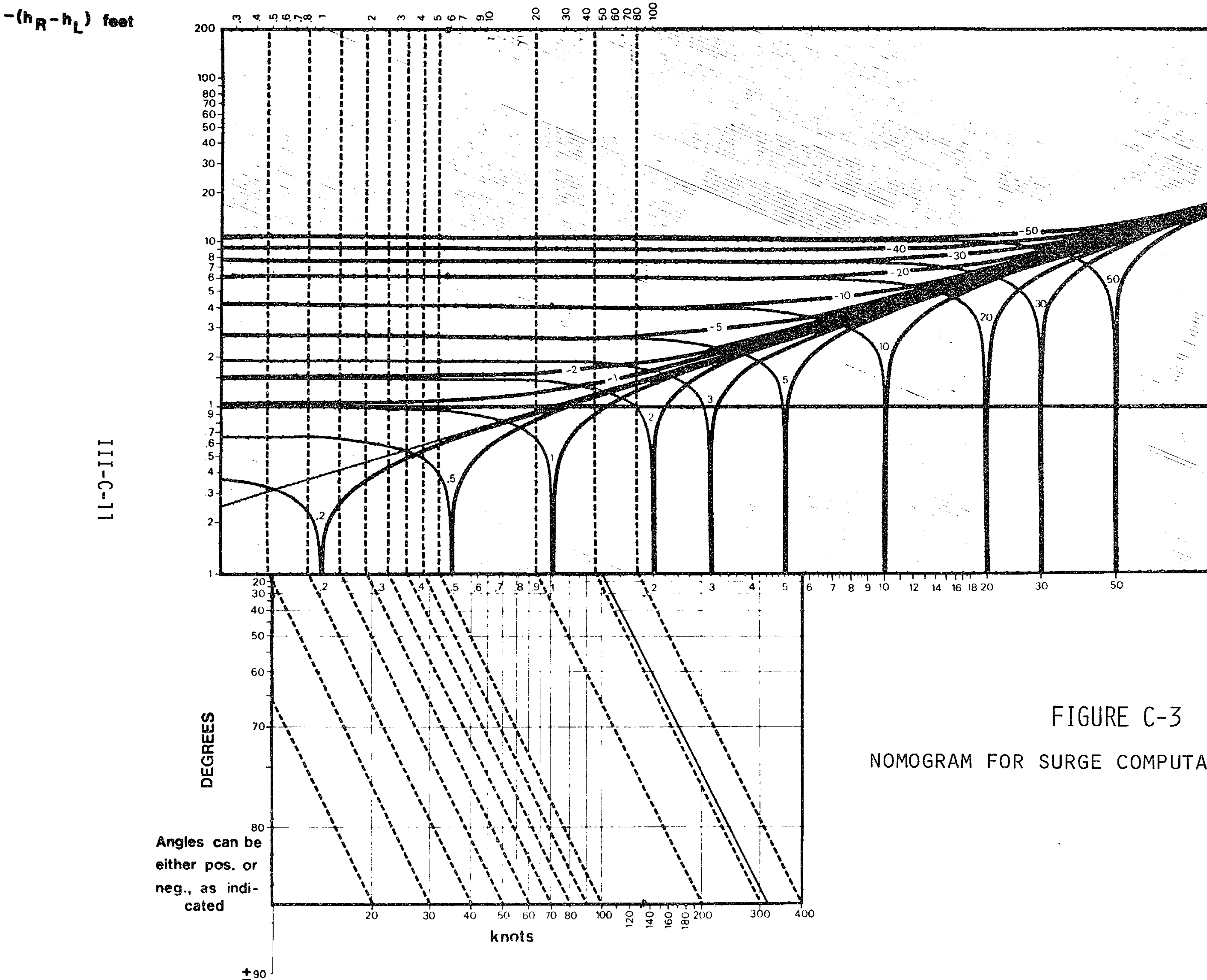

FIGURE C-3

NOMOGRAM FOR SURGE COMPUTATIONS

3.52 Following the slanting lines upward to the left from A to the horizontal line representing the base of the upper nomogram, mark the intersection B and construct the vertical line BC from bottom to top of the upper nomogram.

3.53 From the computation format in 3.0, compute:

(a) $(h' - hg)_L = \frac{(N_L - hg_L) + (N_C - hg_C)}{2}$

(b) $(N_L - N_C)$

3.54 On the vertical axis at the center of the upper nomogram, locate the value of (a). Mark this D. Draw a horizontal line DE to the intersection of BC.

3.55 From E follow the diagonal thin lines to point F on the prominent horizontal line located one third the distance from B to C.

3.56 At the top of the upper diagram locate the value of $(N_L - N_C)$; mark this G. Drop vertically to the line DE (extended if necessary) and mark the point H.

3.57 From H move diagonally and parallel to the white stripes to the intersection of the vertical white stripe. Mark this point J.

3.58 Move horizontally from point J and vertically from point F to the intersection. Mark this P(L). Read the value of P(L) from its interpolated position between those hyperbolas which extend from left to right sloping downward to intersect the base of the upper nomogram where their values are recorded.*

3.59 From the computation format in 3.0, compute

(a) $(h - hg)_R$

(b) $N_C - N_R$

With these values repeat the computations in 3.54 and 3.58 to determine the value of P(R)

---

* *If P(L) lies on the left side of the split nomogram (negative values) then interpolate its value between the hyperbolas which extend from <u>right to left</u> curving downward to intersect the baseline.*

3.60 Compute:

$$N_A = N_B + K_3(P_R - P_L)$$

3.61 Continue computing successive N_A's to the right (inland) for the same time step as in 3.2.

3.62 Complete the profile of saltwater flooding as in 3.4.

3.63 Add the freshwater accumulation to the saltwater flooding in 3.62 to determine the total flooding, D. Proceed as in 3.45 to obtain the design flood depth.

4. SAMPLE COMPUTATION OF N_A. From the computation sheet values in figure B-3, the following is a sample computation of N_A for the step t = -0.5 hours, x = 4 miles.

4.1 The array of known values (Figure B-2) is:

		N_A = ?	
θ = 31.6°	N_L = 11.04'	N_C = 5.26'	N_R = 8.7'
W = 134 mph	hg_L = 2.0'	hg_C = 2.0'	hg_R = 8.5'
		N_B = 4.18'	

(Δt = 30 min.; Δx = 4 mi.)

4.2 <u>Compute N_A using the HP-65 program.</u>

4.21 With HP-65 "on" and in "run" mode, insert the program chip for x = 4 mi.

4.22 Key in θ = 31.6°

STRIKE C--------(read 0.85)

4.23 Key in W = 134

STRIKE R/S-----(read 3.06)

4.24 Key in N_L = 11.04, store in 2;

Key in hg_L = 2.0, store in 3;

Key in N_C = 5.26, store in 4;

Key in hg_C = 2.0, store in 5.

STRIKE A-----(read 2.00)

4.25 Since $(N_R - N_C) > 1.0'$ (cliff effect)

STRIKE D----(read 0.00)

4.26 Key in $N_B = 4.18$

STRIKE R/S-----(read 7.17')

This is the value of N_A.

4.3 <u>Compute N_A using the nomogram.</u>

4.31 From the computation format in 4.1, compute:

$$(h' - hg)_L = \frac{(N_L - hg_L) + (N_C - hg_C)}{2}$$

$$= \frac{9.04 + 3.26}{2} = 6.15'$$

$$(N_L - N_C) = 5.78'$$

4.32 Locate $\theta = 31.6°$ on the vertical axis, lower nomogram. Draw a line horizontally to the right. Locate W = 134 on the horizontal axis, lower nomogram; draw a vertical line upward to intersect the θ value at A.

4.33 Move diagonally to the left from A parallel to the slanting lines to B, the base of the upper nomogram. Draw a vertical line BC to the top of the upper nomogram.

4.34 Locate $(h - hg)_L = 6.15$ on the vertical axis at center of the upper nomogram. Mark this D and draw the horizontal line DE to intersect BC.

4.35 Follow the diagonal thin lines downward to F, the intersection with the prominent horizontal line 1/3 the distance from B to C.

4.36 Locate $N_L - N_C = 5.78'$ on the horizontal line at top of the upper nomogram. Mark this G, and draw GH vertically downward to the intersection of DE.

4.37 From H move diagonally to the right parallel to the white stripes to J, the intersection with the vertical white stripe.

4.38 From J move horizontally and from F vertically to the intersection K.

4.39 Now following the family of hyperbolas enclosing K moving from left to right and sloping downward to the base of the upper nomogram; interpolate the value of K to be 17.5 P(L).

4.40 Since $(hg_R - N_C) > 1.0$ ft., $P(L) \cong 0$.

4.41 $(N_A - N_B) = K_3(0 - 17.5)$

$$= -.17(-17.5) = +2.98$$

4.42 $N_A = N_B + 2.98$

$$= 4.18 + 2.98 = 7.16'$$

DEFINITION OF SYMBOLS

N: height of water above MSL

hg: elevation of terrain above MSL (+), or bottom depth below MSL (-)

Subscripts C, A, B, L, R, referred to N and hg, represent values centered, one step above, below, and to the left and right of a given time and space step, respectively.

Subscripts l, r refer to any left and right grid points later referred to as L, C, and R

x_i: a computation point on the x-axis from x = 0 to x = n

θ: the angle which the wind vector makes with the x-axis measured counterclockwise from the axis

(h' - hg): total water depth

S: distance inland of the building site

S': distance across an inland body of water from the open coast, point O, to the bay shore, P

H': elevation of point Q MSL

H: mean depth of an inland body of water over a strip 8 miles wide along the line OP

h: initial rise defined as 2.0 feet MSL

T: astronomical tidal component at time of max surge, defined as 1.0 feet MSL, 2.1 ft. MLW

CONSTANTS

$K_1 = -.02$

$K_2 = +.001$

$K_3 = -.17$

COMPUTATION OF HYDROGRAPH TIME STEPS N_A WHERE Δt = 30 min.; Δx = 4 mi.

Program listing for HP-65:

STEP NO.	KEYS	STEP NO.	KEYS
1	LBL	26	(-)
2	A	27	RCL 3
3	RCL 8	28	(x)
4	STO 7	29	(·)
5	RCL 2	30	0
6	RCL 3	31	4
7	(-)	32	CHS
8	STO 6	33	(x)
9	RCL 4	34	STO 2
10	RCL 5	35	RCL 6
11	(-)	36	2
12	RCL 6	37	(·)
13	(+)	38	3
14	2	39	3
15	(÷)	40	$\boxed{g}$
16	STO 6	41	5
17	3	42	RCL 1
18	(·)	43	X
19	3	44	RCL 2
20	3	45	(+)
21	$\boxed{g}$	46	STO 3
22	5	47	$\boxed{g}$
23	STO 3	48	6
24	RCL 4	49	$\boxed{f}$
25	RCL 2	50	9

STEP NO.	*KEYS*	*STEP NO.*	*KEYS*
51	STO 2	76	C
52	RCL 3	77	$\boxed{f}$
53	RCL 2	78	5
54	(÷)	79	STO 1
55	STO 8	80	R/S
56	RCL 4	81	ENTER
57	STO 2	82	(x)
58	RCL 5	83	(•)
59	STO 3	84	0
60	RTN	85	0
61	LBL	86	0
62	B	87	2
63	RCL 8	88	(x)
64	RCL 7	89	RCL 1
65	(-)	90	(x)
66	(•)	91	STO 1
67	1	92	RTN
68	7	93	LBL
69	(x)	94	D
70	STO 6	95	RCL 8
71	R/S	96	STO 7
72	RCL 6	97	0
73	(-)	98	STO 8
74	RTN	99	RTN
75	LBL	100	$\boxed{g}$ NOP

SECTION IV

MODEL MINIMUM STANDARD

CHAPTER 1

INTRODUCTION

SECTION 1.1 PURPOSE

1.1.1 APPLICATION: This document is intended to serve as an amendment to the City Building Code in Hurricane Hazard Areas. The provisions contained herein, along with the legally adopted City Building Code shall constitute the minimum building standards and requirements. In case of conflict between the two documents, the most severe requirement, in the judgement of the building official, shall control.

SECTION 1.2 OUTLINE

1.2.1 ADMINISTRATION AND DEFINITIONS: Chapters 2 and 3 define terms and describe implementation procedures including permits, inspection, notice of hurricane hazard, and classification and posting of buildings. Classification and posting of a building declares if the building is safe refuge. In applying for a permit for construction, the owner states the type of hurricane floodproofing desired (from completely floodproof to non-floodproof), and the completed building will be posted accordingly. Due to construction requirements, some of these buildings may be designated and used for safe refuge for vertical evacuation.

1.2.2 DEFINITION AND DELINEATION OF HURRICANE HAZARD ZONES: Chapter 4, along with Annexes A, B and C, defines the various hazard zones and sets out computational procedures for the determination of the zones.

1.2.3 DESIGN PARAMETERS: Chapters 5, 6, 7 and 8 set out the specific design requirements for each hazard zone.

Chapter	Item
5	Wave and Scour
6	Battering by Debris
7	Flooding
8	Wind

1.2.4 STRUCTURAL INTEGRITY: Chapters 9 through 15 set out specific requirements for various types of construction.

Chapter	Item
9	Foundation
10	Masonry
11	Steel and Iron

Chapter	Item
12	Wood
13	Concrete
14	Cladding and Glazing
15	Roofing

SECTION 1.3 USE: In summary, if one wanted to construct a building, the following steps would be required:

1.3.1 Refer to Chapters 2 and 3 for application information and legal procedures.

1.3.2 Refer to Chapter 4 to determine the hazard zone for the particular location.

1.3.3 Refer to Chapters 5, 6, 7 and 8 for design requirements depending upon hazard zone:

Zone	Design Requirements			
	Chapter			
	5	6	7	8
A	X	X	X	X
B		X	X	X
C			X	X
D				X

1.3.4 Refer to Chapters that cover specific construction materials:

Type of Bldg.	9	10	11	12	13	14	15
Light-Gauge Metal Building	X		X		X	X	X
Frame House	X			X	X	X	X
Concrete Block Building	X	X			X	X	X

SECTION 1.4 CONTINUING UPDATE OF CODE: This document is not a perfect work. A continuing effort will be made to keep the requirements in line with new knowledge and actual experience. Therefore, the user is urged to continually update the provisions of this code as information is documented.

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CHAPTER 2

ADMINISTRATION

SECTION 2.1 PURPOSE

2.1.1 APPLICATION: The provisions contained herein shall constitute the minimum building standards and requirements that are applicable to safeguard life or limb, health, property and public welfare by regulating and controlling design, construction, and quality of materials of all buildings and structures which are or will be located in all lands shown within the Hurricane Hazard Area(s). Hereinafter these provisions will be referred to as the "Hurricane Regulations" part of "The Building Code," or in short as "these Regulations."

2.1.2 REGULATORY FLOOD DATUM: For the purpose of these Regulations, the Regulatory Flood Datum, hereinafter referred to as the "RFD," is hereby declared and established for use as the reference datum for determining the elevation above mean sea level to which flood-proofing protection shall be provided.

2.1.3 HURRICANE HAZARD AREAS: For the purpose of these Regulations, the Hurricane Hazard Areas, as further described in Chapter Four, and the RFD are hereby declared and established for use in determining Building Code requirements.

2.1.4 HURRICANE PRECAUTIONS: During such periods as are designated by the National Weather Service as being a hurricane warning or alert, the owner, occupant or user of a property shall take precaution for the securing of buildings and equipment. Canvas awnings and swing signs shall be lashed to rigid construction, tents shall be taken down and stored or lashed to the ground, and such other precautions shall be taken for the securing of buildings or structures or equipment as may be reasonably required.

SECTION 2.2 SCOPE

2.2.1 APPLICATION: These Regulations shall apply to the construction, alteration, and repair of any building or parts of a building or structure in the Hurricane Hazard Area(s) of the ____(city, town, village, etc.)____. Additions, alterations, repairs, and changes of use or occupancy shall comply with all provisions for new buildings and structures as otherwise required in "The Building Code," except as specifically provided in these Regulations.

2.2.2 NONCONFORMING USE: A structure or the use of a structure or premises which was lawful before the passage or amendment of the ordinance but which is not in conformity with the provisions of these Regulations may be continued subject to the following conditions: (1) No such use shall be expanded, changed, enlarged or altered in a way which increases its nonconformity. (2) No structural alteration, addition, or repair to any conforming structure over the life of the structure shall exceed 50 per cent of its value at the time of its becoming a nonconforming use, unless the structure is permanently changed to a conforming use. (3) If such use is discontinued for 6 consecutive months, any future use of the building premises shall conform to these Regulations. The assessor shall notify the zoning administrator in writing of instances of nonconforming uses which have been discontinued for a period of 6 months. (4) If any nonconforming use or structure is destroyed by any means, including Hurricanes, to an extent of 50 per cent or more of its value, it shall not be reconstructed except in conformance with the provisions of these Regulations. (5) Uses or adjuncts thereof which are or become nuisances shall not be entitled to continue as nonconforming uses. (6) Except as provided in "The Building Code," any use which has been permitted as a special exception shall not be deemed a nonconforming use but shall be considered a conforming use. (7) Any alteration, addition, or repair to any nonconforming structure which would result in substantially increasing its hurricane damage or hurricane hazard potential shall be protected as required by these Regulations. (8) The Building Official shall maintain a list of conforming uses, including the date of becoming a nonconforming use and the nature and extent of nonconformity. This list shall be brought up to date annually. (9) The Building Official shall prepare a list of those nonconforming uses which have been hurricane-proofed or otherwise protected in conformance with these Regulations. He shall present such list to the Board of Adjustment, which may issue a certificate to the owner stating that such uses, as a result of these corrective measures, are in conformance with these Regulations.

SECTION 2.3 ALTERNATE MATERIALS AND METHODS OF CONSTRUCTION

2.3.1 APPLICATION: These Regulations are not intended to prevent the use of any materials or methods of construction not specifically prescribed herein or by "The Building Code," provided any such alternate has been approved and its use authorized by the Building Official prior to its incorporation or use in the construction, in accordance with methods and procedures set forth in this code for approval of new materials and special systems of design or construction.

2.3.2 APPROVAL: The Building Official may approve any such alternate, provided he finds the proposed design is satisfactory and complies with the provisions of "The Building Code" and that the material, method, or work offered is, for the purpose intended, at least equivalent to that prescribed in "The Building Code" in quality, strength, effectiveness, fire resistance, durability, and safety. The Building Official shall require that sufficient evidence or proof be submitted to substantiate any claim that may be made regarding its use. If, in the opinion of the Building

Official, the evidence and/or proof is not sufficient to justify approval, the owner or his agent may refer the entire matter to the Board of Appeals.

SECTION 2.4 TESTS

2.4.1 PROOF OF COMPLIANCE: Whenever there is insufficient evidence or proof of compliance with the provisions of these Regulations, or evidence that any material or any construction does not conform to the requirements of these Regulations, or in order to substantiate claims for alternate materials or methods of construction, the Building Official may require tests or test reports as proof of compliance. Tests, if required, are to be made at the expense of the owner or his agent by an approved testing laboratory or other approved agency, and in accordance with approved rules or accepted standards as prescribed in "The Building Code."

2.4.2 ABSENCE OF APPROVED RULES: In the absence of approved rules or other accepted standards, the Building Official shall determine the test procedure or, at his election, shall accept duly authenticated reports from recognized testing authorities or agencies in respect to the quality and manner of use of new materials.

2.4.3 RECORDS: Copies of such tests, reports, certifications, or the result of such tests shall be kept on file in the office the Building Official for a period of not less than three years after the approval and acceptance of the completed structure for beneficial occupancy.

SECTION 2.5 ORGANIZATION AND ENFORCEMENT

2.5.1 RULES AND REGULATIONS: The Building Official is hereby authorized and directed to enforce the provisions of these Regulations as part of "The Building Code." For such purpose he shall have the powers of a police officer.

2.5.2 DEPUTIES: The Building Official may appoint such number of officers, inspectors, and assistants as required. He may deputize such employees as needed to perform the functions of the Building Department.

2.5.3 OFFICIAL RECORDS: The Building Official shall establish and maintain an official record of all business and activities of the department relating to these Regulations, and all such records shall be open to public inspection. He shall keep a permanent, accurate account of all fees and other monies collected and received under these Regulations. The Building Official shall, at least once a year, submit a report to the proper city official covering the work of the Department during the preceding period. Said report shall include detailed information regarding the administration and enforcement of these regulations.

2.5.4 RIGHT OF ENTRY: Whenever it may be necessary to make an inspection to enforce the provisions of these Regulations, the Building Official or his authorized representative may enter such building or premises at all reasonable times to inspect all parts that are or may be subject to flooding or where the potential for hurricane damage exists.

2.5.5 STOP WORK ORDER: Whenever any building work is found to be done contrary to these Regulations, the Building Official shall order the work stopped by notice in writing to the person doing the work.

2.5.6 BOARD OF APPEALS: In order to determine the suitability of alternate materials and methods of construction and to provide reasonable interpretations of the provisions herein, there shall be and is hereby created a Board of Appeals of _____ members. Each member of the Board shall be a licensed professional architect or engineer, or a builder or superintendent of building construction, with at least ten years experience, for five years of which he shall have been in responsible charge of work. At no time shall there be more than two members from the same profession. At least one of the members shall be a licensed structural or civil engineer with architectural engineering experience. The Board shall adopt reasonable rules for its investigations and shall render written decisions to the Building Official.

2.5.7 VALIDITY: It shall be unlawful for any person, firm, or corporation to erect, construct, enlarge, alter, repair, move, improve, remove, convert, or demolish any building or structure in the Hurricane Hazard Area(s), or cause the same to be done, contrary to or in violation of any of the provisions of these Regulations and/or "The Building Code."

2.5.8 VIOLATIONS AND PENALTIES: Any person, firm, or corporation violating any of these provisions shall be deemed guilty of a misdemeanor, and upon conviction thereof shall be punished by a fine or by imprisonment as provided in the laws of the municipality for such misdemeanor, or as specified in "The Building Code."

SECTION 2.6 PERMITS

2.6.1 STATEMENT OF INTENTION TO IMPROVE: The Owner or any registered architect or licensed professional engineer authorized to represent the Owner shall, before preparing final plans for any improvement in the Hurricane Hazard Area(s), file with the Building Official a Statement of Intention to Improve, including a brief description of the type of improvement being considered and giving its precise location, on a form provided by the Building Official. The Building Official shall note on two copies the Hurricane Hazard Zone and the elevation of the RFD at the location of the proposed improvement. One copy of the Statement of Intention to Improve shall be retained by the Building Official until a permit for improvement on the site is approved or one year has elapsed; a second copy shall be returned to the Owner for his use in final siting and design of his improvement. Assignments of the Hurricane Hazard Zone and the RFD elevations at all locations shall be as described in Chapter Four. This information shall be open to public examination at all reasonable times.

2.6.2 PERMITS REQUIRED: No person, firm, or corporation shall erect, construct, enlarge, alter, repair, remove, convert, or demolish any building or structure or any part thereof, or make any other improvement within the Hurricane Hazard Area(s), or cause same to be done, without first obtaining a separate building permit for any such improvement from the Building Official. Ordinary minor repairs may be made without the approval of the Building Official without a permit, provided that such repairs shall not violate any provision of these Regulations or of "The Building Code."

2.6.3 APPLICATIONS: To obtain a permit, the applicant shall first file an application therefore which shall consist of: (1) A description of the work to be covered by the permit including a list of all spaces affected by these Regulations giving flood-proofing class, elevation of RFD, Hazard Zone, floor elevation(s), proposed uses and contents, and references to drawings and specifications which explain the flood-proofing measures that apply to each space. The description shall include an estimate of the total value of the improvement. This description shall be made on a form provided by the Building Official (Figure 1). (2) _____ sets of complete plans and specifications, in addition to plans and specifications required by "The Building Code," except that plans and specifications for any and all proposed improvements in the Hurricane Hazard Area(s) shall be prepared by an engineer licensed by the State to practice as such. All drawings and specifications shall bear the name of the author thereof in his true name, followed by such title as he may be lawfully authorized to use. All plans and sections shall be noted with the proposed flood-proofing class of each space below the RFD including detail drawings of walls and wall openings. (3) _____ copies of the Owner's Contingency Plan, which shall describe in detail all procedures for temporary placement and removal or contingent protection proposed for items in spaces affected by these Regulations including: a. Plans and schedules for items to be removed and locations of places above the RFD to which they will be removed if these contents violate restrictions associated with the flood-proofing class of the space in which they are placed temporarily, including specific organizational responsibilities for accomplishing this removal. b. Procedures, material and equipment for protecting items required to have protection by their flood-proofing class but for which this protection is proposed to be provided contingently, including specific organizational responsibilities for accomplishing this protection. Waivers of restrictions implicitly requested by submission of the Owner's Contingency Plan may be granted by the Building Official as provided by _________. (4) Any other information as reasonably may be required by the Building Official, including computations, stress diagrams, and other data sufficient to show the correctness of the plans.

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Supplementary Application

BUILDING OR STRUCTURE IN FLOOD HAZARD AREA
(To Accompany Application for Building Permit)

City or Town__________ County__________
Location__________
Intended Use__________ Value Of Improvement $______
Type of Construction__________ No. of Stories______
Owner__________ Address__________
Exist.Ground Elev.______MSL; Fin.Ground Elev.______MSL; Reg.Flood Datum Elev.at Site______MSL; RFD Velocity______Ft/Sec
____Floor Elev.______MSL: Proposed Use__________; ____Floor Elev.______MSL: Proposed Use__________
____Floor Elev.______MSL: Proposed Use__________; ____Floor Elev.______MSL; Proposed Use__________

Maximum Loading on Walls:
Non Flood Load__________PSF
Hydrostatic Load__________PSF
Hydrodynamic Load__________PSF
Impact Load__________PSF
Total Flood Load__________PSF

Hydrostatic (Uplift) Pressure on Floor Slabs(Maximum)____PSF
Foundation Type(s)__________
Lowest Footer Elev. (Bottom)__________MSL
Sewage Disposal:___Septic Tank,___Pub.Syst.,___Other(Explain)
Potable Water:___Individual Well___Pub.Syst.,___Other(Explain)

Exterior Wall Construction Type(s):
Above______Floor__________
Above______Floor__________
Above______Floor__________
Above______Floor__________

Floor Construction Type(s):
______Floor__________
______Floor__________
______Floor__________
______Floor__________

Types of Waterproofing__________
Type(s) of Joints: Walls__________Floors__________; Waterstops/Seals(Types): Walls__________Floor__________
Sump Location__________ Sump Type__________
All Tanks and/or Bouyant Equipment Are__________Are Not__________Anchored To Prevent Flotation
Alternate Power Source Is__________Is Not__________Provided For Emergency Operation Of Sump Pump
Sanitary, Drainage & Water Supply Facilities Are______Are Not______Protected From Contamination & Back Flow by Flood Water
Retaining Wall(s) Are__________Are Not__________Used To Protect Building/Structure
Intentional Flooding Is__________Is Not__________Planned For This Building/Structure
Temporary And/Or Emergency Flood Proofing Is__________Is Not__________Planned For This Building/Structure
Building Structure Is__________Is Not__________Protected Against Erosion By Flood Flows
Site Is__________Is Not__________Protected Against Erosion By Flood Flows
Classification Of Building/Structure: FP__________, Primary__________ Secondary__________ Flood Hazard Area.

SPACES: List below all spaces of the building or structure below the Regulatory Flood Datum including their name, room number, and proposed flood-proofing classification (i.e. W1, W2 etc.). List all contents of each space (see Chapter 10 of the Flood-Proofing Regulations). Mark all items which are to be either protected contingently or removed to safe refuge upon receipt of a flood warning with an asterisk (*); all such items must be mentioned in the Owner's Contingency Plan. Attach additional sheets if necessary.

The applicant hereby certifies that the above information is correct and that the plans submitted herewith conform to those submitted for occupancy permit application. The applicant agrees to comply with the provisions of the Zoning Ordinance, the Building Code and all other laws and ordinances affecting the construction and occupancy of this proposed building.

Signature Of Architect/Engineer__________ Address__________

The undersigned will supervise the construction of the work above.

Signature__________

SEAL

Title__________

Date__________

Address__________

(Signature)__________

APPROVED FOR COMPLIANCE WITH BUILDING CODE

Clerk__________

Date__________

Figure 1

2.6.4 ACTION ON PERMIT APPLICATION: The complete application filed by an applicant for a flood-proofing permit, including all of the above listed items, shall be checked by the Building Official. Such plans may be reviewed by other Departments of the ___(city)___ to check compliance with the laws and ordinances under their jurisdiction. The Building Official shall determine that the RFD elevation and Hazard Zone noted in the application are correct in accordance with the Statement of Intention to Improve and that all requirements for the flood-proofing classes selected by the Owner are met. If the Building Official determines that for any space affected by these Regulations, any requirement for particular flood-proofing class, Hazard Zone, or any other requirement of these Regulations has not been met, he shall so indicate on the drawings and a permit shall not be granted. If the Building Official is satisfied that the work described in all parts of the application conforms to the requirements of these Regulations and "The Building Code" and other pertinent laws and ordinances, and that the fees specified in "The Building Code" have been paid, he shall issue a permit therefore to the applicant. When the Building Official issues the permit, he shall endorse in writing or stamp on _____ sets of descriptions, plans and specifications, and the Owner's Contingency Plan "APPROVED" _________(name and date)_____________. _____ sets of the complete application as approved shall be retained by the Building Official for a period of not less than two years after the approval or issuance of a certificate of occupancy for the completed improvement. _____sets of the complete application as approved shall be returned to the applicant, of which one set shall be kept at the building site and available for review by the Building Official at all reasonable times.

2.6.5 ISSUANCE OF PERMIT: The Building Official shall not issue a permit for the partial execution of any improvement until the complete application for the entire improvement has been submitted and approved. The issuance or granting of a permit or approval of an application shall not be construed to be a permit for, or approval of, any violation of these Regulations or of "The Building Code." The issuance of a permit based upon an approved application shall not prevent the Building Official from thereafter requiring correction in such application or any part thereof or from preventing work related to the execution of any improvement from being carried on thereunder when in violation of these Regulations, "The Building Code" or of any other ordinance of the ____(city)_____.

2.6.6 EXPIRATION: Every permit issued by the Building Official shall expire by limitation and shall become null and void if the work authorized by such permit is not commenced within 90 days after issuance date of such permit, or if the work authorized by such permit is suspended or abandoned at any time after the work is commenced for a period of 120 days. Before such work is re-commenced a new permit shall first be obtained, and the fee therefore shall be one-half the amount required for the original permit for such work; and provided, further, that such suspension or abandonment has not exceeded one year, after which, a new application for permit must be submitted and the permit fee shall be based on the total value of all construction work for which the permit is issued.

2.6.7 REVOCATION OF PERMIT: The Building Official may revoke a permit or approval issued under these Regulations in case of any false statement or misrepresentation of fact in the application or on the plans, whenever the permit is issued in error, or whenever the permit is issued in violation of any ordinance or regulation, "The Building Code," or these Regulations.

2.6.8 PERMIT FEES: Building permit fees shall be paid to the Building Official as required and set forth in "The Building Code," and in accordance with the determination of value or valuation under any provision of these Regulations that shall be made by the Building Official.

2.6.9 POSTING OF PERMIT: The building permit shall be posted at the site of operations in a conspicuous place open to public inspection during the entire time of prosecution of the work and until completion of the same.

SECTION 2.7 INSPECTIONS

2.7.1 INSPECTIONS REQUIRED: All construction or work for which a permit is required shall be subject to inspection by the Building Official.

2.7.2 PERIODIC INSPECTIONS: Buildings or structures and parts thereof that contain or utilize contingent or emergency (temporary) type hurricane-proofing elements or devices shall be subject to inspection by the Building Official at intervals of three (3) years or less. The Owner or his agency shall be notified at least 10 days in advance of inspection date and shall be present at the inspection. He shall be responsible for demonstrating the availability, installation, and proper functioning, anchorage and support of all closure assemblies and other contingent or emergency (temporary) hurricane-proofing items. All necessary correction of deficiencies shall be performed within 90 calendar days of the inspection date and at the Owner's expense. Failure to perform the required work within the prescribed time shall be a violation of these Regulations and the applicable part(s) of "The Building Code."

2.7.3 MANDATORY INSPECTIONS: (a) The Building Official, upon notification from the permit holder or his agent, shall make the following inspections and shall either approve that portion of the work completed or shall notify the permit holder or his agent wherein the same fails to comply.

2.7.3.1 FOUNDATION INSPECTION: To be made after necessary excavations have been made, forms erected and reinforcing steel placed.

2.7.3.2 PILE INSPECTION: To be made during the driving of the piles and after all piles are driven and forms and reinforcing steel are in place and tied, and before placing any concrete. (Refer to 2.7.7 SPECIAL INSPECTOR.)

2.7.3.3 REINFORCING INSPECTION: To be made after any reinforcing steel is in place and before placing concrete.

2.7.3.4 FRAME INSPECTION: To be made at each floor level and after all framing, fire blocking, furring and bracing are in place, and plumbing and electrical work are roughed in.

2.7.3.5 ROOFING INSPECTION: To be made after anchor sheet or sheets have been tincapped and before cap sheet is mopped on.

2.7.3.6 CURTAIN WALL INSPECTION: To be made at each floor level after curtain walls are installed and before curtain-wall attachments are concealed.

2.7.3.7 STORE FRONT INSPECTION: To be made after store fronts are installed and before store front attachments are concealed.

2.7.3.8 WINDOW AND GLASS DOOR INSPECTION: To be made after windows and glass doors are installed and before attachments and connections to the building frame are concealed except that for one and two-story buildings this inspection shall not be required.

2.7.3.9 LATHING INSPECTION: To be made after lathing and before plastering, where plastering is a requirement for fire protection, or where suspended overhead.

2.7.3.10 PLUMBING INSPECTION: To be made of the ground work and at each floor. All plumbing work shall be left uncovered and convenient for examination until inspected and approved. Floors shall be left up in all bathrooms and elsewhere above all sanitary plumbing, water-supply and gas-supply piping and other plumbing work until it shall have been examined, tested and approved.

2.7.3.11 ELECTRICAL INSPECTION: To be made at each floor level; and no conduit boxes, panels or other electrical appurtenances shall be covered or concealed until approval shall have been received from the Building Official.

2.7.3.12 SPECIAL INSPECTIONS: To be made of all mechanical installations, signs and awnings immediately upon completion and at such intervals during the progress of the work as the Building Official or this Code may require.

2.7.3.13 OTHER INSPECTIONS: To be made as the owner or contractor or Building Official may reasonably request.

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2.7.3.14 FINAL INSPECTION: To be made after the work is completed and the structure ready for use or occupancy.

2.7.4 No work shall be done on any part of a building or structure or any plumbing, electrical or mechanical installation beyond the point indicated hereinabove for each successive inspection until such inspection has been made and the work approved and the inspector has so indicated on the approved plans or permit card at the job site.

2.7.5 No reinforcing steel or structural framework of any part of any building or structure shall be covered or concealed in any manner whatsoever without the approval of the Building Official.

2.7.6 Inspection requests shall be made to the office of the Building Official and shall provide reasonable time for such inspection to be made. Rejection or refusal to approve the work for reasons of incompleteness, Code violation or inadequacy shall nullify that request for inspection. This work shall be made to comply and the request for inspection repeated as outlined herein. It shall be assumed that the responsible individual or individuals in charge of the work shall have themselves inspected the work and found it to be in compliance with Code requirements before request for inspection is made.

2.7.7 SPECIAL INSPECTOR: (a) The Building Official may require the owner to employ a special inspector for the inspection of the structural framework, or any part thereof, as herein required: 1. Buildings or structures or parts thereof of unusual size, height, design or method of construction and critical structural connections. 2. Pile driving. 3. Windows, glass doors and curtain walls on buildings over two stories. (b) Such special inspector shall be an Architect or Professional Engineer or a duly accredited employee representing either. The special inspector shall be responsible for compliance with this Code and shall submit progress reports and inspection reports to the Building Official. (c) At the completion of the work or project, the special inspector shall submit a Certificate of Compliance to the Building Official, stating that the work was done in compliance with this Code and in accordance with the approved plan or plans; and his duties shall end with the submission of such certificate. Final inspection shall be made by the Building Official before a Certificate of Occupancy is issued.

2.7.8 INSPECTION REPORTS: The Building Official shall keep records of inspections, Certificates of Compliance, results of tests, plans, surveys and Certificates of Occupancy for a period of not less than seven years. Such records shall become a part of the public record and open to public inspection, except as may be elsewhere specifically stipulated.

2.7.9 SPECIAL HURRICANE INSPECTIONS: (a) During such periods of time as are designated by the National Weather Service as being a hurricane alert, all furniture, awnings, canopies, display racks, material and similar loose objects in exposed outdoor locations shall be lashed to rigid construction or stored in buildings. Orders shall be oral or written and shall be given to any person on the premises most logically responsible for maintenance and such orders shall be carried out before winds of hurricane velocity are anticipated. (b) After winds of hurricane velocity are experienced and have subsided, the Building Official shall investigate to determine if damage has occurred to buildings or other structures. (c) No building or other structure or assembly or part thereof which was damaged or collapsed or out of plumb or line shall be repaired or altered or otherwise returned to its original position without inspection and approval by the Building Official.

SECTION 2.8 CERTIFICATE OF USE AND OCCUPANCY

2.8.1 NEW BUILDINGS AND STRUCTURES: No building or structure hereafter constructed in the Hurricane Hazard Area(s), or any portion thereof, shall be used or occupied until the Building Official shall have issued a certificate of use and occupancy.

2.8.2 BUILDINGS OR STRUCTURES HEREAFTER ALTERED: No building or structure in the Hurricane Hazard Area(s) hereafter enlarged, extended or altered, or any portion thereof, shall be used or occupied, and no change in use or occupancy shall have made, until the Building Official shall have issued the certificate of use and occupancy, except that the Building Official may permit lawful use or occupancy to continue upon the submission of evidence that the hurricane hazard or vulnerability of any occupied portions of the structure and its contents will not be increased during the execution of the improvements.

2.8.3 EXISTING BUILDINGS AND STRUCTURES: The Building Official shall issue a certificate of use and occupancy for an existing building or structure located in the Hurricane Hazard Area(s) upon receipt of a written request from the Owner, provided: (1) There are no violations of law or orders of the Building Official pending. (2) It is established after inspection and investigation that the alleged use or occupancy of the building or structure has heretofore existed. (3) There is a positive showing that the continued use or occupancy of a lawfully existing building or structure in the Hurricane Hazard Area(s), without requiring alterations, rehabilitation or reconstruction, does not endanger public safety and welfare. The Building Official shall refuse to issue a certificate of use or occupancy for any existing building or structure in the Hurricane Hazard Area(s) whenever it is found that the building or structure, or any portion thereof or appurtenant thereto, is in an unsafe condition and/or would be potentially unsafe when subjected to floods up to the RFD. He shall, in writing, so notify the Owner, lessee, tenant, occupant and/or agent thereof describing said condition and ordering abatement thereof within a reasonable length of time. Failure to comply with the order of the Building Official shall be a violation of these Regulations and the applicable part(s) of "The Building Code."

2.8.4 CONTENTS OF CERTIFICATE: When a building or structure is entitled thereto, the Building Official shall issue a certificate of use and occupancy that shall certify compliance with the provisions of these Regulations and "The Building Code." Issuance of a certificate does not assign liability to the community.

SECTION 2.9 PUBLIC NOTICE OF HURRICANE HAZARD

2.9.1 PROCEDURE: On or about the first day of May, the Building Official shall alert the public of the existing Hurricane hazard of the ____(city)______. He shall publish or cause to be published a public notice which shall indicate the recorded maximum wind velocity and the elevation of the flood of record together with depths and approximate area(s) of inundation (if known). Said public notice will also contain similar information about the RFD that is established for purposes of these Regulations.

2.9.2 OTHER INFORMATION: The public notice shall emphasize the necessity for maintenance and repair of all contingent hurricane-proofing measures and the probability of occurrence of a hurricane that would cause floods to reach elevations higher than the RFD. It shall advise owners and/or occupants to operate all mechanically and manually operated closure assemblies for doors, windows and utilities openings, emergency electrical generating units, sump pumps, etc., and to check the availability and condition of all temporary closure panels, gaskets and anchorage devices, etc. All organizational, volunteer or assistance groups having responsibilities to act at time of hurricane emergencies shall be advised to review their state of readiness for effective mobilization and implementation of the hurricane emergency plan.

SECTION 2.10 CLASSIFICATION AND POSTING OF BUILDINGS AND STRUCTURES

2.10.1 GENERAL: For administrative purposes of coordination of zoning regulations, inspection of structures, and conduct of emergency public safety operations, all buildings or structures in the Hurricane Hazard Area(s), whether existing or hereafter erected, shall be classified and posted in accordance with this Section. Classification of buildings and structures (FP1, FP2, etc.) is shown in Table 1 and is based upon the flood-proofing classifications of the constituent spaces (W1, W2, etc.) of the structure below the RFD (see Chapter 4) and the means by which these classifications are achieved. Posting shall be accomplished by placards mounted on internal walls at building entrances. For public safety operations, an identification symbol, e.g., FP1, shall be placed on the outside of the building above the RFD so as to be readily visible.

TABLE 1

CLASSIFICATION OF BUILDINGS AND STRUCTURES

Building or Structure Classification	SPACE CLASSIFICATION						
	W1 Completely Dry		W2 Essentially Dry		W3 Flooded with Potable Water	W4 Flooded with Floodwater	W5 Non-Flood-Proofed
	w/o HI*	w/HI*	w/o HI*	w/HI*			
FP1	X		X				
FP2	X	X	X	X			
FP3	X		X		X	X	
FP4	X	X	X	X	X	X	
FP5							X

* *Human Intervention*

2.10.2 STRUCTURE DESIGNED FOR WIND AND COMPLETELY FLOOD-PROOFED (FP1, FP2):

2.10.2.1 FP1 -- Any building or structure located in Hurricane Hazard Area(s) designed in accordance with these Regulations and with no space below the RFD or in which all enclosed spaces below the RFD are classified W1 or W2 without employing any contingent closure, removal, protection, or other measure which requires human intervention for effectiveness in a flood event to obtain those classifications shall be known as a Completely Flood-Proofed Structure and classified FP1. It shall be posted by the Owner with a Type 1 placard, which shall be fastened securely to the structure in a readily visible place.

2.10.2.2 FP2 -- Any building or structure located in a Hurricane Hazard Area designed in accordance with these Regulations and with any space below the RFD and in which all such spaces are classified W1 or W2, but for which at least one or more of the spaces employs any contingent closure, removal, protection, or other measure which requires human intervention for effectiveness in a flood event to obtain those classifications shall be classified FP2. It shall be posted by the Owner with a Type 2 placard, which shall be fastened securely to the structure in a readily visible place above the RFD.

2.10.3 STRUCTURES DESIGNED FOR WIND AND PARTIALLY FLOOD-PROOFED (FP3, FP4):

2.10.3.1 FP3 -- Any building or structure located in a Hurricane Hazard Area designed in accordance with these Regulations and which contains a combination of spaces below the RFD that are classified W1 or W2 which is achieved without human

TABLE 2

SPACE CLASSIFICATION CHART

Flood-Proofing Classes	FLOOD-PROOFING CLASSIFICATION OF SPACES MINIMUM REQUIREMENTS								
	Water-Proofing	Structural Loads	Closure of Openings	Internal Flooding & Drainage	Flooring	Walls and Ceilings	Contents	Electrical	Mechanical
W1 Completely Dry	Type A	Class 1	Type 1	See Section 7.5	Class 1	Class 1	Class 1	See Section 7.9	See Section 7.10
W2 Essentially Dry	Type B	Class 1	Type 1		Class 2	Class 2	Class 2		
W3 Flooded with Potable Water	Type A	Class 2	Type 3		Class 3	Class 3	Class 3		
W4 Flooded with Flood Water	Type C	Class 3	Type 4		Class 4	Class 4	Class 4		
W5 Non-Flood-Proofing	--	--	Type 5		Class 5	Class 5	Class 5		

intervention, and one or more spaces that will be flooded internally (W2 and/or W4), shall be known as a partially flood-proofed structure and be classified FP3. It shall be posted by the Owner with a Type 3 placard which shall be fastened securely to the structure in a readily visible place above the RFD.

2.10.3.2 FP4 -- Any building or structure located in the Hurricane Hazard Area designed in accordance with these Regulations and which contains a combination of spaces below the RFD that are classified W1 or W2 which is achieved with human intervention, and/or one or more spaces that will be flooded internally (W3 and/or W4), shall be classified FP4. It shall be posted by the Owner with a Type 4 placard which shall be fastened securely to the structure in a readily visible place above the RFD.

2.10.4 STRUCTURES DESIGNED FOR WIND BUT NON-FLOOD-PROOFED (FP5): Any existing building or structure located in a Hurricane Hazard Area which contains one or more spaces below the RFD that are not flood-proofed (W5) shall be known as a Non-Flood-Proofed Structure and classified FP5. It shall be posted by the Owner with a Type 5 placard which shall be securely fastened to the structure in a readily visible place.

2.10.5 SAFE REFUGE AREAS: Buildings or structures located in the Hurricane Flood Hazard Area that are provided with area(s) of safe refuge shall have said area(s) posted by the Owner with a Type 6 placard, which shall be securely fastened to the structure in a readily visible place.

2.10.6 PLACARDS: All placards shall be furnished by the Building Official and installed by the owner and shall be replaced immediately if removed, or defaced.

2.10.7 PLACARD TYPES: Placards shall be white rigid plastic or other non-water-susceptible material, _____ inches long and wide, and shall have printed thereon in black letters the information shown in Figure 2.

2.10.8 VIOLATIONS: Failure to comply with the requirements of this section shall be a violation of these Regulations and the applicable part(s) of "The Building Code".

PLACARD TYPES

COMPLETELY FLOOD-PROOFED BUILDING
This building is completely flood-proofed to withstand flooding to the expected high water level of _____ feet MSL. Floor elevation at this point _____ feet MSL.

Type 1

FLOOD-RESISTIVE BUILDING
This building contains areas below the expected high water level of _____ feet MSL which require implementation of pumps or other devices to maintain the required degree of protection. Floor elevation at this point _____ feet MSL.

Type 2

PARTIALLY FLOOD-PROOFED BUILDING
Structural integrity during floods to the expected high water level of _____ feet MSL will be maintained by internal flooding of _____ spaces when flood water reach _____ feet MSL. Floor elevation at this point _____ feet MSL.

Type 3

PARTIALLY FLOOD-RESISTIVE BUILDING
Structural integrity during floods to the expected high water level of _____ feet MSL will be maintained by internal flooding of _____ spaces when waters reach _____ feet MSL. Some areas require implementation of pumps or other devices to maintain the required degree of protection. Floor elevation at this point _____ feet MSL.

Type 4

NON-FLOOD-PROOFED BUILDING

This building is not flood-proofed. Expected high water level is _____ feet MSL.

Floor elevation at this point _____ feet MSL.

Type 5

AREA OF SAFE REFUGE

This space is above the expected high water level of _____ feet MSL, and is authorized as an area of safe refuge for _____ persons.

Floor elevation at this point _____ feet MSL.

Type 6

CHAPTER 3

DEFINITIONS OF TERMS

SECTION 3.1 SCOPE

3.1.1 PURPOSE: For the purpose of these Regulations, certain abbreviations, words, and their derivatives, shall be construed as set forth in this Chapter.

SECTION 3.2 DEFINITIONS

3.2.1 GENERAL: The terms defined in this Chapter have been grouped in accordance with their main uses under the headings Administrative, Physical, and Regulatory.

3.2.2 ADMINISTRATIVE:

3.2.2.1 ACCESSORY USE OR STRUCTURE -- a use or structure on the same lot with, and of a nature customarily incidental and subordinate to, the principal use or structure.

3.2.2.2 BUILDING OFFICIAL -- the officer charged with the administration and enforcement of the Building Code and these Hurricane-proofing Regulations or his regularly authorized deputy.

3.2.2.3 HURRICANE HAZARD ZONES -- As defined in Chapter 4.

3.2.2.4 FREEBOARD -- a factor of safety usually expressed in feet above a design flood level for flood protective or control works. Freeboard tends to compensate for the many unknown factors that could contribute to flood heights greater than the height calculated for a selected size flood and floodway conditions such as wave action, bridge opening and floodway obstructions, and the hydrological effects of urbanization of the watershed.

3.2.2.5 HABITABLE ROOM -- a space used for living, sleeping, eating or cooking, or combination thereof, but not including bathrooms, toilet compartments, closets, halls, storage rooms, laundry and utility rooms, basement recreation rooms and similar spaces.

3.2.2.6 NONCONFORMING USE -- a building or structure, or the use thereof, which was lawful before the passage or amendment of the (ordinance, resolution, act) but which is not in conformance with the provisions of these Regulations.

3.2.2.7 OWNER -- any person who has dominion over, control of, or title to an artificial or natural obstruction.

3.2.2.8 REGULATORY FLOOD -- a flood which is representative of large floods known to have occurred generally in the area or reasonably characteristic of what can be expected to occur in a particular hurricane. This hurricane is generally being recognized and accepted nationally by Federal and non-Federal interests as one with an average frequency of occurrence on the order of once in 100 years.

3.2.2.9 REGULATORY FLOOD DATUM (RFD) -- established plane of reference from which elevation and depth of flooding may be determined for specific locations of the floodplain. It is the Regulatory Flood plus a freeboard factor of safety established for each particular area which tends to compensate for the many unknown and incalculable factors that could contribute to greater flood heights than that computed for a Regulatory Flood.

3.2.2.10 SUBDIVISION -- the partitioning or dividing of a parcel or tract of land.

3.2.3 PHYSICAL:

3.2.3.1 ARTIFICIAL OBSTRUCTION -- any obstruction which is not a natural obstruction.

3.2.3.2 CHANNEL -- a natural or artificial watercourse of perceptible extent, with definite bed and banks to confine and conduct continuously or periodically flowing water. Channel flow thus is that water which is flowing within the limits of the defined channel.

3.2.3.3 FILL -- the placing, storing, or dumping of any material, such as (by way of illustration but not of limitation) earth, clay, sand, concrete, rubble, or waste of any kind upon the surface of the ground which results in increasing the natural ground surface elevation.

3.2.3.4 FLOOD -- an overflow of lands adjacent to a river, stream, ocean, lake, etc., not normally covered by water. Otherwise it is normally considered as any temporary rise in stream flow or stage that results in significant adverse effects in the vicinity. Adverse effects may include damages from overflow of land areas, backwater effects in sewers and local drainage channels, creation of unsanitary conditions, soil erosion, deposition of materials during flood recessions, rise of ground water coincident with increased stream flow, contamination of domestic water supplies, and other problems.

3.2.3.5 FLOOD CREST -- the maximum stage or elevation reached by the waters of a flood at a given location.

3.2.3.6 FLOODPLAIN -- the area, usually low lands, adjoining the channel of a river, stream or watercourse or ocean, lake, or other body of standing water which has been or may be covered by floodwater.

3.2.3.7 FLOOD-PROFILE -- a graph or a longitudinal profile showing the relationship of the water surface elevation of a flood to location along a stream or river.

3.2.3.8 FLOOD-PROOFING -- a combination of structural changes and/or adjustments incorporated in the design and/or construction and alteration of individual buildings, structures or properties subject to flooding primarily for the reduction or elimination of flood damages.

3.2.3.8.1 PERMANENT FLOOD-PROOFING -- permanent protection shall be provided against the flood which does not depend upon any judgment, flood forecast, or action to put flood protection measures into effect.

3.2.3.8.2 CONTINGENT (OR PARTIAL) FLOOD-PROOFING -- contingent measures shall not be effective unless, upon receipt of a warning or forecast, some minimal action shall be required to make the flood-proofing measures operational.

3.2.3.8.3 EMERGENCY (OR TEMPORARY) FLOOD-PROOFING -- emergency measures shall be, upon receipt of a warning or forecast, either improvised just prior to or during an actual flood or carried out according to an established emergency plan of action.

3.2.3.9 NATURAL OBSTRUCTION -- natural obstruction shall mean any rock, tree, gravel, or analogous natural matter that is an obstruction and has been located within the floodway by a nonhuman cause.

3.2.3.10 REACH -- a hydraulic engineering term to describe longitudinal segments of a stream or river. A reach will generally include the segment of the floodplain where flood heights are primarily controlled by man-made or natural floodplain obstructions or restrictions. In an urban area, the segment of a stream or river between two (2) physically identifiable points on the stream centerline would most likely be designated as a reach.

3.2.3.11 STRUCTURE -- anything constructed or erected on the ground, or attached to the ground, including but not limited to the following: docks, dams, fences, mobile homes, sheds and buildings.

3.2.3.12 UNDERCLEARANCE -- the lowest point of a bridge or other structure over or across a river, stream, or watercourse that limits the opening through which water flows. This is referred to as "low steel" in some regions.

3.2.3.13 WATERCOURSE -- any natural or man-made depression with a bed and well-defined banks two feet or more below the surrounding land serving to give direction to a current of water at least nine months of the year or having a drainage area of one square mile or more.

3.2.4 REGULATORY:

3.2.4.1 BUILDING CODE -- the regulations adopted by a local governing body setting forth standards for the construction, addition, modification and repair of buildings and other structures for the purpose of protecting the health, safety, and general welfare of the public.

3.2.4.2 SUBDIVISION REGULATIONS -- regulations and standards established by a local unit of government with authority granted under a state enabling law, for the subdivision of land in order to secure coordinated land development, including adequate building sites and land for vital community services and facilities such as streets, utilities, schools and parks.

CHAPTER 4

HURRICANE HAZARD ZONES

SECTION 4.1 DEFINITION OF THREAT AND HAZARD ZONES: A severe hurricane will pose several classes of hazards along the Texas coastline and extending inland distances which vary with coastal configuration.

4.1.1 WIND: maximum windspeeds (fastest mile) up to 140 mph at a height of 30 feet, increasing with height in accordance with the one-seventh power law to a maximum several hundred feet above the surface. Peak gust speeds will exceed the sustained values by variable percentages. These gusts are considered in the tables in Chapter 8.

4.1.2 STORM SURGE: (three sources of damage potential) (1) Scour due to currents and wave action, including washovers; (2) Battering due to waterborne debris; and (3) Flooding due to combinations in rises in sea level from storm surge and inland runoff from heavy rains and riverine discharges.

4.1.3 In terms of these threat classes, the following coastal hazard zones are defined as the basis for the design of applicable model building codes:

ZONE A:
(1) 140 mph sustained winds
(2) scouring action affecting foundation design
(3) battering from floating debris
(4) flooding (still water levels from expected hurricane inundation more than one foot above building grade level)

ZONE B: Same as Zone A except without scour

ZONE C: Same as Zone A except without scour and battering

ZONE D: 140 mph sustained winds at C-D boundary, diminishing as an exponential function of distance* to 100 mph at inland boundary

SECTION 4.2 COMPUTATION OF REGULATORY FLOOD: The Regulatory Flood may be computed by adding the peak storm surge elevation and the inland rainfall backwater curve elevation as further described in this section. Refer to Annex A, B, and C.

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* $V_D = 100 + \frac{40}{1+d^2}$, *where* V_D = *wind speed in Zone D*

d = *distance inland from C-D boundary*

SECTION 4.3 GEOGRAPHICAL IDENTIFICATION OF HAZARD ZONES

4.3.1 ZONE A: Area of washover and scour.

4.3.1.1 Narrow, low segments of barrier islands and peninsulas that have been, are presently or have a high potential of being reached as a result of elevated water levels that generally exist during storms. (Ref: Bureau of Economic Geology, University of Texas.)

4.3.1.2 A zone extending between Gulf beaches and a line of at least 300 feet from the maximum elevation immediately adjacent to the beach (e.g., dune crest or crest of sand and shell ramp).

4.3.1.3 A zone along low-lying (less than 10 feet) unprotected (nonbulkheaded) bay shorelines extending at least 200 feet inland from the highest elevation from the shoreline.

4.3.1.4 Areas within 200 feet of unprotected (nonbulkheaded) navigation channels on peninsulas and barrier islands.

4.3.1.5 Areas with sand substrate subject to hurricane flooding of greater than 3 feet with current velocities greater than 3 feet per second for one hour or more during the rise and fall of the surge.

4.3.2 ZONE B: In the absence of washover channels and extensive scour, battering from waterborne debris will be expected to occur and will comprise the basis for defining Zone B.

4.3.2.1 On barrier islands and peninsulas, a zone extending inland from the most landward foredune line or line of highest elevation and on low-lying shorelines with primarily clay substrate, a zone extending inland from the shoreline at least 500 feet regardless of building density.

4.3.2.2 In areas where hurricane flooding is expected to be greater than 4 feet, building density is not greater than one major structure per acre, and effective wind fetch of greater than one mile.

4.3.3 ZONE C: In the absence of the above conditions but where "still water" hurricane flood levels are in excess of one foot.

4.3.4 ZONE D: This zone is concerned solely with wind forces on structures. Zone D is a strip beginning at the boundary with Zone C and extending inland to a point where the sustained hurricane winds are expected to reach 100 mph using the inverse relationship:

$V_D = 100 + \frac{40}{1+d^2}$, where V_D = wind speed in Zone D

d = distance inland from C-D boundary

CHAPTER 5

WAVE AND SCOUR ACTION

SECTION 5.1 GENERAL: Buildings and other structures shall not be constructed in Hazard Zone A unless positive provision is made either (a) to prevent movement or scour of underlying soil, or (b) to safeguard the structure in the event that such movement does occur.

5.1.1 PREVENTION OF SOIL MOVEMENT: Prevention of underlying soil movement may be accomplished by retaining structures or bulkheads adequately designed to resist, in addition to the vertical loads acting thereon, incident lateral earth pressures, surcharges and hydrostatic loadings corresponding to the maximum high-water level.

5.1.2 SAFEGUARDING STRUCTURE WHEN SOIL MOVEMENT OCCURS: In areas where scour and soil movement can occur if retaining structures or bulkheads are not provided, the structure shall be designed to be supported by properly designed pile foundations with due consideration being given to column action of piling in the event of scour, lateral loads on piling, and uplift capacity of piling when subjected to uplift loads by water or wind action.

5.1.3 SOIL INVESTIGATION: All plans for new structures shall bear a statement as to the nature and character of the soil under the structure. Where the capacities of the soil are not known, examinations of subsoil conditions by borings or other tests may be required and evaluation of such soil investigations shall be made by a Professional Engineer. (Ref: Sec. 9.2)

5.1.4 DESIGN OF FOUNDATIONS, RETAINING STRUCTURES, AND BULKHEADS

All pile foundations, retaining structures and bulkheads in coastal areas subject to wind, wave and tidal action shall be designed by a Professional Engineer registered in the State of Texas. Records of penetration and bearing of all piles during installation shall be kept by the special inspector or Professional Engineer supervising the pile driving operations, bulkhead, or retaining structure installations. Copies of these records shall be submitted to the authority having jurisdiction.

SECTION 5.2 STRUCTURAL REQUIREMENTS

5.2.1 GENERAL: All buildings and structures shall be designed and constructed to resist the erosive and corrosive effects of the elements and where applicable to withstand the horizontal and vertical forces or loads required by "The Building Code" and, in addition, all loads prescribed in this section, without exceeding the prescribed allowable stresses.

5.2.2 LOADS:

5.2.2.1 WATER: As specified in Section 7.3.3.

5.2.2.2 WAVES: The maximum wave force shall be calculated by using the maximum period. The most critical wave force, so determined, shall be used in the design. In case the natural period of vibration of the structure exceeds three seconds, dynamic analysis shall be performed to determine whether a resonance with the exciting wave forces is possible.

5.2.2.2.1 WAVE DESIGN INFORMATION: Wave force design assumptions and calculations shall be submitted to the Building Official.

5.2.2.3 BATTERING: As specified in Section 6.2.

5.2.2.4 WINDS: As specified in Chapter 8.

5.2.3 ALLOWABLE STRESSES: Allowable stresses for structural design shall be in accordance with the Building Code.

5.2.4 STRUCTURES - LOCATION, TYPE, GENERAL SPECIFICATIONS

5.2.4.1 LOCATION: Structure location must conform to other local, county, state and federal building and zoning regulations as well as these regulations.

5.2.4.2 GENERAL: If the proposed type (material and geometry) or method of construction does not have an experience record sufficient to justify approval, the Building Official may require special tests or demonstrations to prove the acceptability of the project.

5.2.4.3 BULKHEADS AND SEAWALLS

5.2.4.3.1 LOCATION: In order to obtain uniformity of the shoreline, bulkheads should be located so as not to interfere with the requirements of the Texas Open Beaches Act. Locations of bulkheads other than along the official bulkhead line may be approved to meet proper land use requirements and if it is shown that no detriment to adjoining property will result. In no case shall the actual bulkhead alignment differ more than two inches from the approved alignment. In no case shall a bulkhead project seaward beyond the official bulkhead line except within the above-stated tolerance. Bulkheads proposed between two properties where bulkheads already exist shall be designed to connect such bulkheads. Bulkheads proposed adjacent to property not bulkheaded shall be designed to return along the side property line a distance sufficient to protect the backfill and prevent damage to adjacent property, but not less than 25 feet along the ocean and bay or 10 feet along canals, rivers, and other water areas. The return wall shall be protected from erosion by riprap or slope pavement.

5.2.4.3.2 TYPE OF WALLS: The use of vertical face bulkheads will normally be limited to the bay front or inland waterways. Seawalls on the front and walls along sand beaches subject to wave action are to be an approved sloping high energy absorbing type, or vertical with energy-absorbing rubble mound on the face subject to wave action. The toe of the wall should be located sufficiently landward of the mean high-water line to prevent any immediate erosion of the foreshore area, and not less than 200 feet from the mean low-water shoreline on Gulf beaches subject to the Open Beaches Act; otherwise not less than 50 feet from same. Whenever the beach in front of an existing vertical wall has eroded to such extent that water reaches the bottom of the wall at mean high tide, a rubble mound shall be placed in front of the wall; and existing vertical walls along sand beaches, when in need of major repairs, shall not be replaced unless a rubble mound be constructed in front of them.

5.2.4.3.3 GENERAL SPECIFICATIONS: All bulkheads shall have a concrete cap designed to withstand the various loads placed upon it. The cap shall be large enough to provide no less than four inches of concrete cover between the piles, panels or masonry and nearest exterior face of cap. The elevation of the top of the cap shall be above the official flood criteria. (Such criteria provide for a minimum fill elevation, but not for storm wave heights.) Other cap elevations may be approved but only when land usage, proximity of buildings, and effect on adjacent property have been considered. Safety curbs or guardrails shall be provided for bulkheads adjacent to roadways. Handrails shall be provided for bulkheads adjacent to walkways. Cables or steel rods used in tiebacks must be protected by at least three inches of concrete encasement if the cable or rod is less than one inch in diameter. Tiebacks not encased in concrete are to be protected by coating and wrapping with bituminous or other corrosive-resistant material. Anchors for tiebacks, whether piles or other types, shall bear on undisturbed or well compacted soil and shall be designed to provide adequate horizontal support. Precast concrete panels of tee-pile and panel bulkheads shall have the foot of the panels placed in a manner that will prevent undermining of the backfill material. Fill material placed on the water side of a bulkhead shall not be considered to offer any passive resistance when such fill is subject to erosion. Gravity type bulkheads of stone and concrete combination will be permitted, provided they are constructed of no less than 40 percent cast-in-place concrete by cross sectional area and volume.

5.2.4.4 PIERS AND DOCKS

5.2.4.4.1 LOCATION: Piers and docks at right angles to the shoreline, or nearly so, shall be located not closer to the side property line, or said line extended, than a distance equal to the length of the pier or dock itself, provided however, no such distance shall be less than 10 feet. Where the zoning is residential or where the area is subdivided into tracts smaller than one acre each, piers and docks are to be located within the middle one-half of the water frontage.

5.2.4.4.2 TYPES: Structures such as piers which are to project beyond the bulkhead line, if allowed, shall be of an open type construction. Wharves, piers, or docks of solid fill construction will be approved only where such construction will not extend seaward of the approved bulkhead line.

5.2.4.4.3 GENERAL SPECIFICATIONS: In areas where the zoning is residential or in areas where no tract is larger than one acre, piers and docks shall be no more than 30 feet wide. In no case shall piers or docks obstruct navigation or interfere with drainage facilities. The projection of a pier or dock into a restricted waterway such as a canal, river, creek or basin shall be no greater than 10 feet or 20% of the waterway width, whichever is smaller, but shall comply with any other laws or regulations that may exist. Furthermore, the General Land Office's approval may be given for piers projecting into open water areas such as bays and sounds provided the projecting pier does not obstruct navigation or encroach upon the rights of adjacent property owners.

5.2.4.5 GROINS

5.2.4.5.1 LOCATION: Groins are to be located so that the entire system of groins will provide the maximum benefit without adverse effects. Groins shall be anchored sufficiently landward to prevent flanking.

5.2.4.5.2 TYPES: Groins shall be either very low impermeable nonadjustable or impermeable <u>adjustable</u>, designed and maintained in adjustable condition for their entire life. The use of permeable groins shall be limited to special conditions.

5.2.4.5.3 GENERAL SPECIFICATIONS: Groins may be used to stabilize the beach if adjoining beaches are not adversely affected. Groins shall be impermeable, and adjustable to meet variations in natural conditions, and to produce the desired elevation of the beach. Adjustable groins shall be maintained at elevations in accord with actual beach needs and development of desirable changes of the beach profile, and so as to avoid damage to adjacent beaches. In no case shall the top of such groins be set higher than 2 feet above the beach profile. Impermeable, nonadjustable groins shall not extend seaward beyond the mean low water line, and their top elevation shall not be higher than 6 inches above the beach profile. Groins must be constructed or adjusted low enough to provide pedestrian access across them. Consideration of the degree of beach protection to be provided by proposed groins, and the acceptability of such installations, will be based primarily on the following factors: Direction and Volume of Littoral Drift; Wave Force and Direction; Wind Force and Direction; Land Usage; Type of Bulkhead; Type of Groin; and Spacing and Length of Groins. A complete coastal engineering study may be required before approval is given to the number, type, and location of groins.

5.2.4.6 BEACH NOURISHMENT: Artificial nourishment of sand beaches or creation of new beach area are treated as construction projects. Typical profiles for such projects consist of a 50-foot level berm at elevation 6 ft. MSL; a 1 on 20 slope from there to MLW; and a 1 on 30 slope seaward to existing bottom. Special agreement between the upland owner proposing such a project and the building official may be required in order to adequately protect and permanently safeguard any public rights at the proposed site.

5.2.4.7 JETTIES AND BREAKWATERS: Jetties and breakwaters shall be designed in accordance with the latest issue of the U.S. Army Corps of Engineers' Technical Report No. 4 entitled "Shore Protection, Planning and Design."

5.2.4.8 MOORING PILES AND BUOYS: All mooring piles and buoys shall be placed within the limits of the owner's water frontage and shall be located in a manner not to interfere with navigation. Outer mooring piles and buoys shall not obstruct a navigable waterway except as permitted by the appropriate agency having jurisdiction over the waterway.

5.2.4.9 BOAT SLIPS AND BOATHOUSES: Boat slips and boathouses to be located on private property require approval and permit from the Building and Zoning Department. Bulkheads proposed to be constructed for retaining the banks of the boat slip shall meet the requirements of this section of the manual. The location of boat slips shall conform to the same requirements as for piers and docks. Boathouses may be constructed over boat slips or as a separate structure subject to the following conditions: (a) The boathouse is not used as a dwelling, guest house or servant's quarters unless specially constructed as such to the requirements of the Building and Zoning Department; (b) The boathouse does not extend into a water area a distance greater than that permitted for a dock or pier; and (c) The overall size of the boathouse does not exceed 25 feet in width, 45 feet in length, or 18 feet in height, except commercial marinas and drydocks may be permitted larger boathouses constructed in compliance with applicable zoning and building regulations.

5.2.5 INFORMATION REQUIRED ON AND FOR THE PREPARATION OF CONSTRUCTION PLANS: Construction plans must be prepared by an engineer registered in Texas. Plans shall be arranged and numbered as a set and contain all (or applicable portions) of the following: (1) Plan, elevation, and sections showing the complete structure; (2) Details of structural components including precast members, structural connections, steel reinforcement, and expansion joints; (3) Complete description of all materials to be used; (4) Design loading and minimum penetration of piles; (5) Location control: a. Horizontal control referred to a section line, road, or permanent landmark, and including property lines and the Official Bulkhead Line. b. Vertical control referred to U.S. Coast and Geodetic Survey Datum (MSL) including elevations landward, soundings in water areas, and the mean high water line; and (6) Graphical representation of test borings or soil profile parallel to and within five feet of proposed structures.

CHAPTER 6

BATTERING BY DEBRIS

SECTION 6.1 GENERAL: Buildings and other structures constructed in Hazard Zone B shall be designed in accordance with the provisions of this regulation and the "Building Code."

6.1.1 Buildings designated as "Safe Refuge" and constructed in Hazard Zone B shall be designated for special battering loads. All other structures, except as noted, in Hazard Zone B shall be designed for normal battering loads.

SECTION 6.2 BATTERING LOADS

6.2.1 NORMAL BATTERING LOADS: Normal battering loads are those which relate to isolated occurrences of floatable objects of normally encountered sizes striking buildings or parts thereof. The normal battering load shall be considered as a concentrated load acting horizontally at the RFD or at any point below it, equal to the impact force produced by a 1,000 pound mass traveling at a velocity of 10 feet per second and acting on a one-square-foot surface of the structure.

6.2.2 SPECIAL BATTERING LOADS: Special battering loads are those which relate to large conglomerates of floatable objects, either striking or resting against a building, structure or parts thereof. Where special battering loads are likely to occur (as in Hazard Zone B), such loads shall be considered in the design of buildings designated "Safe Refuge." Unless a rational and detailed analysis is made and submitted for approval by the Building Official, the intensity of the load shall be taken as 500 pounds per foot acting horizontally over a one-foot-wide horizontal strip at the RFD or at any level below it. Where natural or artificial barriers exist which would effectively prevent these special battering loads from occurring, the loads may be ignored in the design.

6.1.3 EXTREME BATTERING LOADS: Extreme battering loads are those which relate to large floatable objects and masses such as runaway barges or collapsed buildings and structures, striking the building, structure, or component under consideration. It is considered impractical to design buildings having adequate strength for resisting extreme battering loads. Accordingly, except for special cases when exposure to these loads is highly probable and the resulting damages are severe, no allowances for these loads need be made in the design.

SUBJECT TO REVISION

CHAPTER 7

FLOODING

SECTION 7.1 FLOOD-PROOFING CLASSIFICATION OF SPACES BELOW THE REGULATORY FLOOD DATUM

7.1.1 SCOPE

7.1.1.1 GENERAL: The flood-proofing classification of a space is determined by the degree of protection required under these Regulations to permit its intended use. The flood-proofing class of a space for which temporary placement or contingent protection measures are approved assumes that these measures are in effect during a flood and defines the resulting relationship of protection to use.

7.1.1.2 ASSIGNMENT OF FLOOD-PROOFING CLASSES: Assignment is made by the Owner at the time of application for a permit and is subject to the approval of the Building Official. Every space of an improvement in a Flood Hazard Area which impinges in whole or part upon the RFD shall have a flood-proofing class assigned to it, and all requirements associated with a flood-proofing class shall be met by the space to which they apply in addition to all other requirements of these Regulations and the Building Code.

7.1.2 DESCRIPTIONS OF FLOOD-PROOFING CLASSES

7.1.2.1 CLASSIFICATIONS: The following descriptions of the five flood-proofing classes are approximate and general; more precise specification of the requirements associated with each class is given in Table 2 of the following section.

7.1.2.2 COMPLETELY DRY SPACES (W1): The spaces shall remain completely dry during flooding to the RFD; walls shall be impermeable to passage of water and water vapor. Permitted contents and interior finish materials are virtually unrestricted, except for high-hazard type uses or human habitation. No portion of the building or structure that is below the RFD, regardless of structure or space classification, shall be used for human occupancy or for storage of any property, material, or equipment that might constitute a safety hazard when contacted by flood waters. Structural components shall have capability of resisting hydrostatic and hydrodynamic loads and the effects of buoyancy.

7.1.2.3 ESSENTIALLY DRY SPACES (W2): These spaces shall remain essentially dry during flooding to the RFD; walls shall be substantially impermeable to water, but may pass some water vapor or seep slightly. Contents and interior finish materials are restricted when hazardous or vulnerable under these conditions. Structural components shall have capability of resisting hydrostatic and hydrodynamic loads and the effects of buoyancy.

7.1.2.4 SPACES INTENTIONALLY FLOODED WITH POTABLE WATER (W3): These spaces will be flooded internally with potable water provided by the Owner in order to maintain the building's structural integrity by equalizing pressures on structural components during flooding to the RFD; walls shall be sufficiently impermeable to prevent the passage, infiltration, or seepage of contaminated floodwaters. Contents and interior finish materials are restricted when hazardous or vulnerable under intentional flooding conditions.

7.1.2.5 SPACES FLOODED WITH FLOODWATER (W4): These spaces will be flooded with floodwater (contaminated) by automatic means or are otherwise partially exposed to the unmitigated effects of the flood. Although there are minimal structural requirements for walls and other structural components, contents and interior finish materials are restricted to types which are neither hazardous nor vulnerable to loss under these flooding conditions. (Most spaces in existing buildings would have this classification if provided with a suitable automatic flooding system. Carports, loading platforms, open crawl spaces, porches and patios would generally fall into this classification.)

7.1.2.6 NON-FLOOD-PROOFED SPACES (W5): A non-flood-proofed space in an existing building or structure is defined as a space which fails to meet the requirements of any of the above-described classifications.

7.1.3 THE SPACE CLASSIFICATION CHART

7.1.3.1 GENERAL: Table 2 indicates the various degrees of protection required to permit uses of spaces for each flood-proofing class. Although spaces must meet the requirements shown for each element of flood-proofing, the chart in itself shall not be construed as being exhaustive with respect to all requirements imposed by these Regulations. In disputes arising over the interpretation of this chart, the written provisions of these Regulations shall be considered as definitive.

7.1.3.2 SEPARATION OF SPACES WITH DIFFERENT FLOOD-PROOFING CLASSIFICATIONS: Any two adjacent spaces below the RFD having different flood-proofing classes shall be separated by a barrier meeting the requirements for the space with the lower-numbered classification. In addition, any opening below the RFD between two adjoining spaces shall be provided with a closure meeting the requirements for the space with the lower-numbered classification.

SECTION 7.2 WATERPROOFING

7.2.1 SCOPE

7.2.1.1 PURPOSE: This section shall govern the design, use and methods of construction and materials with respect to obtaining, for a given space, the degree of protection against water, water vapor, and waterborne contamination determined by the vulnerability or hazard potential of the contents and interior finish materials to meet its flood-proofing classification.

7.2.1.2 PERFORMANCE STANDARDS: Three types of waterproofing are defined herein as to the degree to which they satisfy a standard of dryness. If any material or method of construction meets the functional performance standard defining a type of waterproofing construction it shall be considered as satisfying the requirements of the section. For the purpose of these Regulations, the detailed specification of Type A waterproofing construction, as contained in this section, shall be interpreted as a guide to measures which are reasonable prerequisites for attaining this standard of dryness.

7.2.2 TYPE A CONSTRUCTIONS

7.2.2.1 PERMEABILITY: Type A waterproofing constructions are completely impermeable to the passage of external water and water vapor under hydrostatic pressure of flooding to the RFD. Type A waterproofing construction shall consist of either a continuous membrane satisfying paragraph 7.2.2.2, integrally waterproofed concrete satisfying paragragh 7.2.2.3, or a continuous interior lining satisfying paragraph 7.2.2.4.

7.2.2.2 TYPE A MEMBRANE CONSTRUCTION: Type A membrane waterproofing forms a continuous external impervious lining to protect a structure with a concrete floor slab and concrete or reinforced concrete masonry unit walls. It shall comply with the following requirements for structural prerequisites, materials, and installation.

7.2.2.2.1 STRUCTURAL PREREQUISITES:

7.2.2.2.1.1 CONTINUITY OF STRUCTURE: Structural slabs below the grade shall be continuous under perimeter walls to prevent differential settlement and shall be designed to act monolithically with the walls; reinforced concrete masonry unit walls shall be connected rigidly to slabs with reinforcing steel.

7.2.2.2.1.2 PROJECTION OF SLAB: Where a slab is continuous under perimeter walls, it shall project not less than six (6) inches beyond the outside of the wall in order to provide space for joining horizontal and vertical membranes.

7.2.2.2.1.3 COLUMNS: Where columns occur, there shall be no vertical discontinuity or abrupt change in slab cross sections. Where slab thicknesses change, they shall do so gradually, and the effects of pressure distribution on the thinner portions of the slab cross section shall be considered.

7.2.2.2.1.4 PROTECTION: All membranes shall be installed on exterior surfaces of perimeter walls. For floor slabs, the membrane shall be installed between the structural slab and wearing surface or otherwise placed on a nonstructural concrete sub-base at least two (2) inches in thickness to protect the membrane and insure its flatness; in the latter case (Figure 3) a two (2) inch thick sand-cement screed shall be placed over the membrane before laying reinforcing steel for the structural slab. If a floor membrane is sandwiched between two structural slabs, the membrane shall be positioned at a location that will not subject it to excessive overstress conditions.

7.2.2.2.1.5 PILE FOUNDATIONS: When spaces are supported on pile foundations, the pile shall be positively connected to the member which it supports (column, wall, beam, etc.) in order to prevent overturning or displacement of the building. The penetration required for this positive connection must be protected by keyways, asphaltic bitumen pocket, or other accepted engineering design. A reinforced concrete sub-slab of not less than four (4) inches thick shall be provided over the entire area in order to receive the membrane. If the weight of the structure is such as to prohibit overturning and displacement of the structure thereby permitting complete separation between the pile caps and the floor slab, the pile caps shall be interconnected with stabilizing beams, cast monolithically with the sub-slab.

7.2.2.2.2 MATERIALS: For the purpose of these Regulations, a membrane shall be any layered sheet construction of tar/asphalt bitumen and felts, at least 3-ply in thickness neoprene-coated nylon fabric, other approved sheet material, or multiple applied hydrolithic coatings of asphaltic bitumens. All applicable ASTM standards shall apply to Type A membranes and their component parts.

7.2.2.2.2.1 PERMEABILITY: Type A membrane shall permit passage of no more than three (3) pounds of water per 1,000 square feet in 24 hours at 40 psi.

7.2.2.2.2.2 PLASTIC WATERPROOFING MATERIALS: Various plastic materials, including, among others, polyethylene, PVC, polyurethane, and polyisobutylene, shall be permitted in sufficient thicknesses in sheets or coatings. In certain cases the Building Official may require less protection beneath plastic than the concrete sub-base required in paragraph 7.2.2.2.1.4.

7.2.2.2.3 INSTALLATION:

7.2.2.2.3.1 APPLICATION: All Type A membrane waterproofing shall be applied by a certified roofing or waterproofing contractor.

7.2.2.2.3.2 TURNS: Turns at corners, both vertical and horizontal, shall be made with chamfers and fillets of not less than two (2) inches dimension on any side.

7.2.2.2.3.3 SEAMS: Membrane seams or overlaps, if any, shall be thoroughly interleaved and protected in accordance with accepted practice, but in no case shall seams or overlaps be less than two (2) inches in any direction.

7.2.2.2.3.4 PIPES: Points where pipes or ducts penetrate waterproofed construction shall be designed to be watertight in accordance with accepted engineering practice.

7.2.2.2.3.5 JOINTS: Membranes shall be continous across expansion, control, and construction joints, which shall have waterstops of rubber, copper, plastic, or other suitable materials.

7.2.2.2.3.6 PROTECTION: Membranes on walls shall extend at least three (3) inches above the RFD of the protected space and shall be attached with a reglet or covered with protective masonry at its upper termination. To protect all wall membranes during backfill operations, protection of not less than 1/2-inch thickness of cement parging, plastic sheets, or other rigid non-cellulose material, installed in a workmanlike manner, shall be provided; however, in large projects or where the protection required above may not be adequate, the Building Official may require protection by some other means.

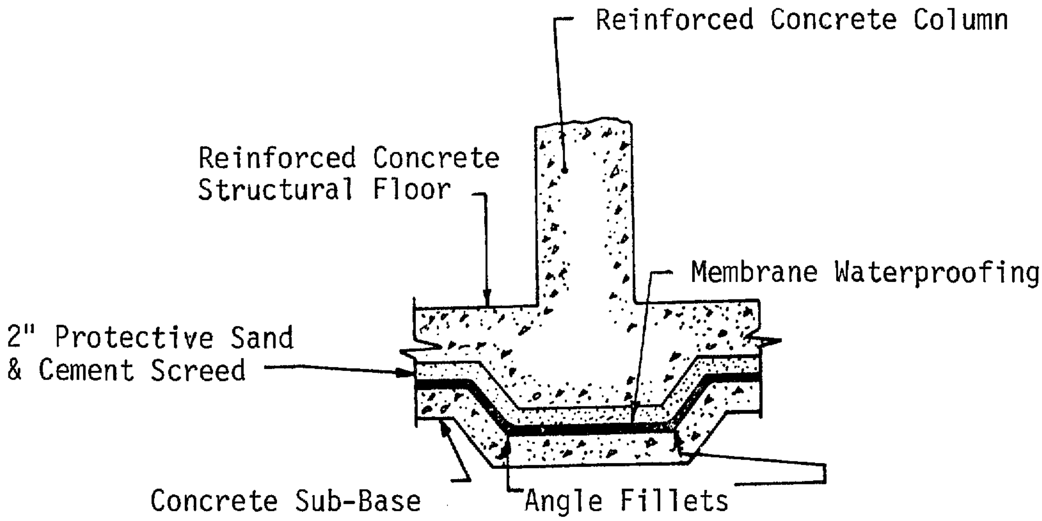
7.2.2.2.3.7 EXCAVATION: Excavation preceding construction shall extend a minimum distance of 24 inches beyond the exterior wall lines to facilitate construction operations. In built-up areas where this requirement cannot be met, excavation limits will be as designated by the Building Official.

7.2.2.3 TYPE A INTEGRALLY WATERPROOFED CONCRETE CONSTRUCTION: Type A integrally waterproofed concrete construction shall comply with the following requirements for structural prerequisites, materials, and installation.

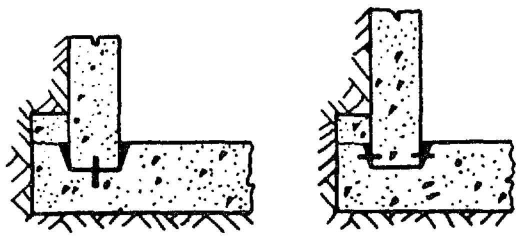
7.2.2.3.1 STRUCTURAL PREREQUISITES:

7.2.2.3.1.1 CONTINUITY OF STRUCTURE: Structural slabs shall be continuous under perimeter walls. Slabs shall be designed to act monolithically with perimeter walls, or otherwise shall carry them non-rigidly in a recess with mastic V fillings and waterstops. (Figure 4.)

7.2.2.3.1.2 DEFLECTIONS: To prevent increases of permeability in tension zones, the maximum deflection of any structural slab or perimeter wall shall not exceed 1/500 of its shorter span.



TYPE "A" MEMBRANE WATERPROOFING IN FLOOR SLABS



(a) (b)

NON-RIGID PERIMETER WALL AND FLOOR SLAB CONNECTIONS

7.2.2.3.1.3 COLUMNS: Where columns occur, there shall be no vertical discontinuity or abrupt change in slab cross section. Where slab cross sections change, they shall do so gradually, and the effects of pressure distribution on the thinner portions of the slab cross section shall be considered.

7.2.2.3.2 MATERIALS:

7.2.2.3.2.1 STRENGTH: All Type A integrally waterproofed concrete shall have a seven-day compressive strength of at least 3,000 psi and a 28-day compressive strength of 4,000 psi.

7.2.2.3.2.2 WATERPROOFING ADMIXTURES: If an approved waterproofing admixture is used, the cement content required to achieve the strength specifications may not be reduced by more than 10%. Approved admixtures shall not reduce the compressive strength of the concrete and shall act as a densifier and/or to increase workability.

7.2.2.3.2.3 JOINTS: Expansion joints shall be keyed and provided with waterstops. Construction joints shall be provided with waterstops and shall be thoroughly roughened and cleaned before continuation of concrete placement.

7.2.2.3.2.4 PROTECTION OF FRESH CONCRETE: When potentially aggressive groundwater conditions exist, the Building Official may require the protection of fresh concrete from contact with groundwater for a minimum of 14 calendar days. Protection shall be accomplished either by the removal of groundwater or by the application of a temporary membrane or surface coating (e.g., bitumen or tar emulsion) which, however, need not meet standards for permanent protection.

7.2.2.4 TYPE A INTERIOR LININGS: A Type A interior lining forms a continuous internal impervious barrier to protect a structure with a concrete floor slab and concrete or reinforced concrete masonry unit walls. All Type A interior linings shall conform to the following requirements for structural prerequisites, materials and installation.

7.2.2.4.1 STRUCTUAL PREREQUISITES:

7.2.2.4.1.1 CONTINUITY OF STRUCTURE: Structural slabs below grade shall be continuous under perimeter walls to prevent differential settlement and shall be designed to act monolithically with the walls; reinforced concrete masonry unit walls shall be connected rigidly to slabs with reinforcing steel.

7.2.2.4.1.2 COLUMNS: Where columns occur, there shall be no vertical discontinuity or abrupt change in slab cross sections. Where slab thicknesses change, they shall do so gradually, and the effects of pressure distribution on the thinner portions of the slab cross section shall be considered.

7.2.2.4.1.3 DEFLECTIONS: To prevent cracking of the interior lining, the maximum deflection of any structural slab or perimeter wall to which the lining is applied shall not exceed 1/500 of its shorter span.

7.2.2.4.2 MATERIALS: For the purpose of these Regulations, an interior lining shall be any continuous coating, parging, or rendering of a cementious or other approved waterproofing material or compound with adequate structural strength and impermeability to serve its intended purpose. All relevant ASTM standards shall apply to Type A interior lining materials.

7.2.2.4.2.1 PERMEABILITY: Type A interior linings shall permit the passage of no more than three (3) pounds of water per 1,000 square feet in 24 hours at 40 psi.

7.2.2.4.3 INSTALLATION:

7.2.2.4.3.1 APPLICATION: All Type A interior lining waterproofing shall be applied by a certified roofing or waterproofing contractor.

7.2.2.4.3.2 TURNS: Turns at corners, both vertical and horizontal, shall be made with fillets of not less than two (2) inches dimension on any side.

7.2.2.4.3.3 PIPES: Points where pipes or ducts penetrate waterproofed construction shall be designed to be watertight in accordance with accepted engineering practice.

7.2.2.4.3.4 JOINTS: Interior linings shall be continuous across expansion, control and construction joints, which shall have waterstops of rubber, copper, plastic, or other suitable material.

7.2.2.4.3.5 VERTICAL EXTENT: Interior linings on walls shall extend at least 3 inches above the RFD of the protected space.

7.2.2.4 EXISTING SPACES: Spaces in existing buildings or structures which become subject to these Regulations may be approved as having Type A waterproofing upon submission by the Owner of plans and specifications for these spaces prepared by a licensed architect or engineer; however, the Building Official shall make a thorough inspection of actual site conditions and may require that tests be made to demonstrate the adequacy of the work before granting this approval.

7.2.3 TYPE B CONSTRUCTIONS

7.2.3.1 PERMEABILITY: Type B waterproofing constructions shall be substantially impermeable but may pass water vapor and seep slightly during flooding to the RFD. Large cracks, openings, or other channels that could permit unobstructed passage of water shall not be permitted. In no case shall there be permitted the accumulation of more than four (4) inches of water depth in such a space during a 24-hour period if there were no devices provided for its removal. However, sump pumps shall be required to control this seepage.

7.2.3.2 UPGRADING EXISTING SPACES: Spaces with Type B waterproofing construction may be upgraded to Type A through the installation of a continuous exterior or interior lining or a combination of both, which the Building Official may approve as meeting the requirements for permeability of Type A waterproofing.

7.2.3.2.1 INSPECTIONS: The Building Official shall make inspections prior to and upon completion of this work before approving the completed work as meeting Type A waterproofing requirements. The Building Official may require that tests be made to demonstrate the adequacy of the work before granting this approval.

7.2.4 TYPE C CONSTRUCTIONS

7.2.4.1 NON-WATERPROOFED: Type C waterproofing constructions are any which do not satisfy the requirements for Type A or B in 7.2.2 and 7.2.3 respectively.

7.2.4.2 UPGRADING OF SPACES: Non-waterproofed spaces may be upgraded to Type A or B waterproofing when the Building Official shall approve such work as meeting the standard for Type A or B in 7.2.2 and 7.2.3.

7.2.4.2.1 INSPECTIONS: The Building Official shall make inspections prior to, during, and upon completion of this work before approving the improvement as Type A or B waterproofing, and may require tests be made to demonstrate the adequacy of the work before granting this approval.

<u>SECTION 7.3 STRUCTURAL REQUIREMENTS</u>

7.3.1 SCOPE

7.3.1.1 GENERAL: All buildings and structures covered by these Regulations and all parts thereof shall be capable of resisting all loads required by "The Building Code" and, in addition, all loads prescribed in this section, without exceeding the prescribed allowable stresses.

7.3.2 CLASSES OF LOADS

7.3.2.1 CLASS 1 LOADS: Reflect the probable effects of flooding on structures which are waterproof (W1 or W2). These loads shall be calculated in complete accordance with this section and shall include all water, impact, and soil loads specified herein.

7.3.2.2 CLASS 2 LOADS: Reflect the probable effects of flooding on structures which include internal flooding as a means of structural protection and which shall be so flooded in accordance with Section 7.5. These loads shall be calculated in accordance with this section except that only hydrodynamic and impact loads must be considered when the interior and exterior water levels are equal.

7.3.2.3 CLASS 3 LOADS: Apply to buildings or structures which are to be flooded with floodwater either internally by automatic means or externally in partially exposed areas. For such internal flooding, Class 3 loads shall coincide with those of Class 2. For partially exposed spaces, however, any dependent or supporting structural components shall be designed for Class 1 or 2 loads if they are also structural components of any adjacent enclosed space, whichever is required; isolated or free-standing columns or walls shall meet all criteria of 7.3.9.2.3.

7.3.3 WATER LOADS

7.3.3.1 TYPES: Water loads, as defined herein, are loads or pressures on surfaces of the buildings or structures caused and induced by the presence of floodwaters. These loads are of two basic types: hydrostatic and hydrodynamic.

7.3.3.2 HYDROSTATIC LOADS: Hydrostatic loads are those caused by water either above or below the ground surface, free or confined, which is either stagnant or moves at very low velocities, or up to five (5) feet per second. These loads are equal to the product of the water pressure times the surface area on which the pressure acts. The pressure at any point is equal to the product of the unit weight of water (64 pounds per cubic foot) multiplied by the height of the water above the point or by the height to which confined water would rise if free to do so. Hydrostatic pressures at any point are equal in all directions and always act perpendicular to the surface in which they are applied. For the purpose of these Regulations, hydrostatic loads are subdivided into the following types:

7.3.3.2.1 VERTICAL LOADS: These are loads acting vertically downward on horizontal or inclined surfaces of buildings or structures, such as roofs, decks, or floors, and walls, caused by the weight of flood waters above them.

7.3.3.2.2 LATERAL LOADS: Lateral hydrostatic loads are those which act in a horizontal direction, against vertical or inclined surfaces both above and below the ground surface and tend to cause lateral displacement and overturning of the building, structure, or parts thereof.

7.3.3.2.3 UPLIFT: Uplift loads are those which act in a vertically upward direction on the underside of horizontal or sloping surfaces of buildings or structures, such as basement slabs, footings, floors, decks, roofs and overhangs. Hydrostatic loads acting on inclined, rounded or irregular surfaces may be resolved into vertical or uplift loads and lateral loads based on the geometry of the surfaces and the distribution of hydrostatic pressures.

7.3.3.3 HYDRODYNAMIC LOADS: Hydrodynamic loads, for the purpose of these Regulations, are those induced on buildings or structures by the flow of floodwater moving at moderate or high velocity around the buildings or structures or parts thereof above ground level. Such loads may occur below the ground level when openings or conduits exist which allow free flow of floodwaters. Hydrodynamic loads are basically of the lateral type and relate to direct impact loads by the moving mass of water, and to drag forces as the water flows around the obstruction. Where application of hydrodynamic loads is required, the loads shall be computed or estimated by recognized and authoritative methods.

7.3.3.3.1 CONVERSION TO EQUIVALENT HYDROSTATIC LOADS: For the purpose of these Regulations, and for cases when water velocities do not exceed 10 feet per second, dynamic effects of the moving water may be converted into equivalent hydrostatic loads by increasing the depth of water to the RFD by an amount dh, on the headwater side and above the ground level only, equal to:

$$dh = \frac{a\,V^2}{2g}, \text{ Where}$$

V is the average velocity of the water in feet per second;
g is the acceleration of gravity, 32.2 feet per second per second;
a is the coefficient of drag or shape factor. (The value of a, unless otherwise evaluated, shall not be less than 1.25.)

The equivalent surcharge depth dh shall be added to the depth measured between the design level and the RFD and the resultant pressures applied to, and uniformly distributed across, the vertical projected area of the building or structure which is perpendicular to the flow. Surfaces parallel to the flow or surfaces wetted by the tailwater shall be considered subject to hydrostatic pressures for depths to the RFD only.

7.3.3.4 INTENSITY OF LOADS:

7.3.3.4.1 VERTICAL LOADS: Full intensity of hydrostatic pressures caused by a depth of water between the design level and the RFD applied on all surfaces involved.

7.3.3.4.2 LATERAL LOADS: Full intensity of hydrostatic pressures caused by a depth of water between the design elevation(s) and the RFD applied over all surfaces involved, both above and below ground level, except that for surfaces exposed to free water the design depth shall be increased by one foot.

7.3.3.4.3 UPLIFT: Full intensity of hydrostatic pressures caused by a depth of water between the design level and the RFD acting on all surfaces involved, unless provisions are made to reduce uplift intensities as permitted in 7.3.8.

7.3.3.4.4 HYDRODYNAMIC LOADS: Hydrodynamic loads, regardless of method of evaluation, shall be applied at full intensity over all above-ground surfaces between the ground level and the RFD.

7.3.3.5 APPLICABILITY: For the purpose of these Regulations, hydrostatic loads shall be used in the design of buildings and structures exposed to water loads from stagnant floodwaters for conditions when water velocities do not exceed five (5) feet per second, and for buildings and structures or parts thereof not exposed or subject to flowing water. For buildings and structures, or parts thereof, which are exposed and subject to flowing water having velocities greater than five (5) feet per second, hydrostatic and hydrodynamic loads shall apply.

7.3.5 ALLOWABLE SOIL PRESSURES

7.3.5.1 APPLICABILITY: Under flood conditions, the bearing capacity of submerged soils is affected and reduced by the buoyancy effect of the water on the soil. For foundations of buildings and structures covered by these Regulations, the bearing capacity of soils shall be evaluated by a recognized acceptable method. Expansive soils should be investigated with special care. Soils which lose all bearing capacity when saturated, or become "liquified," shall not be used for supporting foundations. If a detailed soils analysis and investigation is not made, and if bearing capacities of the soils are not evaluated as required above, allowable soil pressures permitted in "The Building Code" may be used, provided those values are reduced 50%.

7.3.6 STABILITY

7.3.6.1 OVERTURNING: All buildings and structures covered by these Regulations and all parts or elements thereof shall be proportioned to provide a minimum factor of safety of 1.50 against failure by sliding or overturning when subjected to flood-related loads or combined loads. The required stability shall be provided by the normal resistive loads allowed by "The Building Code," such as frictional resistance between the foundations and the soil, passive earth pressure, batter and vertical piles and permanent anchors which may be provided. For the purpose of providing stability, only the dead load shall be considered effective. No use shall be made of any resistance, either as weight or frictional or passive, from soils which could be removed or displaced by excavation, scour or other causes. Similarly, no use shall be made of frictional resistance between the foundation and the underlying soil in the case of structures supported on piles.

7.3.6.2 FLOTATION: The building or structure, and all appurtenances or components thereof not rigidly anchored to the structure, shall have enough weight (deadload) to resist the full or reduced hydrostatic pressures and uplift from floodwater at the RFD with a factor of safety of 1.33. For provisions governing reduced uplift intensities, see 7.3.7. In cases when it is not practical to provide the required factor of safety against flotation by weight alone, the difference shall be made up by providing dependable and permanent anchors that meet the approval of the Building Official. Elements which depend on anchorage to other portions of the structure shall be anchored to a portion or portions of the structure which have the required factor of safety against flotation from all contributing elements subject to uplift. Apportionment of uplift and resisting forces shall be made by a recognized method of structural analysis in accordance with accepted engineering practice.

7.3.6.3 ANCHORAGE: Any building and structure as a whole which lacks adequate weight and mass to provide the required factors of safety against overturning, sliding, and flotation shall be dependably and permanently anchored to the ground. In addition, all elements of a building or structure, such as wall, floor slabs, girders, beams, columns and other members, shall be dependably connected or anchored to form an adequate structural system to support the individual members and all the applied loads. Provision of adequate anchorage is also essential and required for all tanks and vessels, sealed conduits and pipes, lined pits and sumps and all similar structures which have negligible weight of their own.

7.3.7 REDUCTION OF UPLIFT PRESSURES

7.3.7.1 GENERAL: Uplift forces, in conjunction with lateral hydrostatic forces constitute the most adverse flood-related loading on buildings and structures and elements thereof. Their combined effect determines to a major extent the requirements for weight and anchorage of a structure as a whole to assure its stability against flotation, sliding and overturning. When uplift forces are applied to structural elements of a building or structure, such as footings, walls, and particularly basement slabs, they generally constitute the critical loading on such elements. In the interest of providing economical solutions to the basic problem of structurally flood-proofing buildings and structures, it is permissible under these Regulations to make provisions for effectively reducing uplift forces acting under the structure. The plans and design data submitted to the Building Official for approval shall show complete and detailed procedures, assumptions, analyses and design information, and specific provisions to be incorporated in the work for accomplishing the proposed reduction in uplift. Data and design procedures shall be based on recognized and acceptable methods of foundation drainage and waterproofing. Such provisions shall include, but are not limited to, the following items, used alone or in combination, as conditions will dictate.

7.3.7.2 IMPERVIOUS CUTOFFS: Impervious cutoffs are barriers installed below the ground line and externally to the perimeter of the building or structure for the purpose of decreasing seepage quantities and/or reducing existing gradients. Such cutoffs must, in all cases where floodwaters will rise above the ground level, be connected by suitable impervious blankets or membranes to the walls of the building or structure. Cutoffs may consist of interlocking steel sheeting, compacted barrier of impervious soil, grouted or injected cutoffs, impervious wall of interconnected concrete piles or panels, and similar seepage barriers, used alone or in combination.

7.3.7.3 FOUNDATION DRAINAGE: Where impervious cutoffs are provided or where suitable foundation conditions exist, effective drainage and relief of uplift pressures under buildings and structures can be achieved. These foundation materials must be free-draining and have the desired degree of permeability. For the purpose of these Regulations, foundation drainage is intended to consist of the provision of drainage blankets, trenches, and, in all cases, drain tiles or perforated drainpipes adjacent to footings and under floor slabs. Other methods of foundation drainage, such as by means of sumps, well points, or deep wells can be used for special applications. Drainpipes shall discharge into a sump or suitable collection structure, where the water is collected and ejected by sump pumps.

7.3.7.4 SUMPS AND PUMPS: Spacing, sizing and determination of depth of sumps shall be consistent with and correlated to the intended drainage system, the estimated amount of seepage and drainage yield.

7.3.8 REQUIREMENTS FOR OTHER FLOOD-PROOFING METHODS

7.3.8.1 METHODS: A building shall be considered as being completely flood-proofed if the lowest elevation of all space(s) within the building perimeter is above the RFD as achieved by: (1) building on natural terrain beyond the RFD limit line on natural undisturbed ground, (2) building on fill, (3) building on stilts, and (4) protection by dikes, levees and/or floodwalls. These methods may be used alone or in combination to achieve the required degree of flood-proofing. Data and design procedures shall, in all cases, be based on recognized and acceptable methods of the applicable disciplines involved, and the following additional requirements.

7.3.8.2 FLOOD-PROOFING BY ELEVATING THE BUILDING

7.3.8.2.1 NATURAL TERRAIN: In addition to the requirements of "The Building Code," the building shall be located not less than 50 feet back from the line of incidence of the RFD on the ground, foundation design shall take into consideration the effects of soil saturation on the performance of the foundation, the effects of floodwaters on slope stability shall be investigated, normal access to the building shall be by direct connections with areas above the RFD and all utility service lines shall be designed and constructed as required to protect the building and/or its components from damage or failure during a flooding event to the RFD.

7.3.8.2.2 BUILDING ON FILL: The building and all parts thereof may be constructed above the RFD on an earth fill. Prior to placement of any fill or embankment materials, the area upon which fill is to be placed, including a five-foot strip measured horizontally beyond and contiguous to the toe line of the fill, shall be cleared of standing trees and snags, stumps, brush, down timber, logs and other growth, and all objects including structures on and above the ground surface or partially buried. The area shall be stripped of topsoil and all other material which is considered unsuitable by the Building Official as foundation material. All combustible and noncombustible materials and debris from the clearing, grubbing and stripping operations shall be removed from the proposed fill area and disposed of at locations above the RFD and/or in the manner approved by the Building Official. Fill material shall be of a selected type, preferably granular and free-graining, placed in compacted layers. Fill selection and placement shall recognize the effects of saturation from floodwaters on slope stability, uniform and differential settlement, and scour potential. The minimum elevation of the top of slope for the fill section shall be at the RFD. Minimum distance from any point of the building perimeter to the top of the fill slope shall be either 25 feet or twice the depth of fill at that point, whichever is the greater distance. This requirement does not apply to roadways, driveways, playgrounds, and other related features which are not part of the building proper. Fill slopes for granular materials shall be no steeper than one vertical on one and one-half horizontal, unless substantiating data justifying steeper slopes are submitted to the Building Official and approved. For slopes exposed to flood velocities of less than five (5) feet per second, grass or vine cover, weeds, bushes and similar vegetation undergrowth will be considered to provide adequate scour protection. For higher velocities, stone or rock slope protection shall be provided.

7.3.8.2.3 BUILDING ON "STILTS": The building may be constructed above the RFD by supporting it on "stilts" or other columnar type members, such as columns, piers, and in certain cases, walls. Clear spacing of support members, measured perpendicular to the general direction of flood flow, shall not be less than eight (8) feet apart at the closest point. The "stilts" shall, as far as practicable, be compact and free from unnecessary appendages which would tend to trap or restrict free passage of debris during a flood. Solid walls, or walled-in columns are permissible if oriented with the longest dimension of the member parallel to the flow. "Stilts" shall be capable of resisting all applied loads as required by "The Building Code" and all applicable flood related loads as required herein. Bracing, where used to provide lateral stability, shall be of a type that causes the least obstruction to the flow and the least potential for trapping floating debris. Foundation supports for the "stilts" may be of any approved type capable of resisting all applied loads, such as spread footings, mats, piles and similar types. In all cases, the effect of submergence of the soil and additional floodwater-related loads shall be recognized. The potential of surface scour around the stilts shall be recognized and protective measures provided, determined by a registered Professional Engineer.

7.3.8.3 PROTECTION BY DIKES, LEVEES, AND FLOODWALLS: The building shall be considered a floodproofed type when it is protected from floodwaters to the RFD by means of dikes, levees, or floodwalls, either used alone or in combination, as necessary. This protection may extend all around the building where all surrounding ground is low, or on one or more sides where high ground (above the RFD) exists on the remaining sides. Regardless of type and method of construction, dikes, levees, and floodwalls shall be designed and constructed in accordance with recognized and accepted engineering practice and methods. They shall have adequate strength and stability to resist all applied loads and shall provide an effective watertight barrier up to the RFD.

7.3.8.3.1 DIKES AND LEVEES: Dikes and levees shall be constructed of suitable selected material, placed and compacted in layers to a section that has the required stability and impermeability. Prior to start of placement operations, the area on which the dike or levee is to be constructed shall be prepared as required in 7.3.8.2.2. In cases where underlying materials are highly pervious, it may be necessary to provide impervious cutoffs. A filter blanket, drainage ditch and/or trench shall be provided along the interior toe of the construction to collect seepage through the dike or levee. All seepage and storm drainage shall be collected at a sump or sumps where it may be pumped out over the dike. Normal surface runoff within and into the diked area during nonflood periods may be discharged through appropriate drainage pipes and culverts through the dike. Such culverts shall have a dependable flap, slide gate, or backflow preventing device which would close either automatically or manually to prevent backflow during a flood. Scour protection measures for dikes and levees shall comply with the requirements of 7.3.8.2.2. Clearance from the toe of the dike or levee to the building shall be a minimum of 20 feet or twice the height of the dike or levee above the interior finished grade, whichever is greater.

7.3.8.3.2 FLOODWALLS: Floodwalls may be constructed of concrete, steel sheet piling, or other suitable structural materials. Regardless of type, the wall shall have adequate strength and stability to resist the applied loads. The provisions of 7.3.8.3.1 shall be followed, as applicable, regarding removal of unsuitable materials, provision of impervious cutoffs, provision of seepage and storm drains, drainage ditches, sumps and sump pumps, and the minimum clearances from the floodwall to the building. It shall be recognized in the drainage provisions that substantial amounts of leakage may occur through the interlock of a steel sheet piling wall. Adequate expansion and contraction joints shall be provided in the walls. Expansion joints will be provided for all changes in wall direction. Contraction and expansion joints in concrete walls shall be provided with waterstops and joint sealing material both in the stem and in the base. Steel sheet piling walls may be encased in concrete for corrosion protection or shall be coated with a coal tar epoxy coating system and periodically inspected and maintained. Steel sheet piling walls may be used as the impervious core of a dike.

SECTION 7.4 CLOSURE OF OPENINGS

7.4.1 SCOPE

7.4.1.1 GENERAL: Openings in exterior and interior walls of buildings or structures in a Flood Hazard Area which are wholly or in part below the RFD shall be provided with waterproof closures meeting the requirements of this section.

7.4.2 TYPES OF CLOSURES

7.4.2.1 CLASSIFICATION: Closures shall be classified into five types according to their compatibility with the waterproofing standards of the various flood-proofing classes.

7.4.2.1.1 TYPE 1 CLOSURES: Shall form a complete sealed barrier over the opening that is impermeable to the passage of water at the full hydrostatic pressure of a flood to the RFD.

7.4.2.1.2 TYPE 2 CLOSURES: Shall form essentially dry barriers or seals, allowing only slight seepage during the hydrostatic pressure conditions of flooding to the RFD.

7.4.2.1.3 TYPE 3 CLOSURES: Shall form barriers or seals that are impermeable to the passage of waterborne contamination under equalized pressure conditions.

7.4.2.1.4 TYPE 4 CLOSURES: Shall form barriers to the passage of flood-carried debris and the loss of floating items from the interior, but are not required to form impermeable seals.

7.4.2.1.5 TYPE 5 CLOSURES: Are those of existing spaces which do not meet the requirements of any of the above described types, but are in use as required by "The Building Code."

7.4.3 REQUIREMENTS

7.4.3.1 DESIGN STANDARDS FOR CLOSURE ASSEMBLIES: The structural capacity of all closures shall be adequate to support all flood loads acting upon its surface. Closure assemblies may be fabricated of cast iron, steel, aluminum, or other adequate and durable structural material, provided with a continuous support around its perimeter, and shall be attached to the building or structure at its immediate location of use, i.e., hinged, or slides, or in a vertical recess. The closure device shall be capable of being set in place with minimal manual effort. Seals, where required, shall be gasketed pressure types permanently anchored or attached to the structure or to the closure assembly. Closures designed to lift into vertical recesses for storage when not in use, and/or located so that the open position of the assembly will not impede fire exit or the functioning of a fire closure assembly, shall be supported in the open position by auxiliary supports of safety latches that can be released at times of flooding. In the closed position the closure assembly shall engage fixed wedging blocks that will force the closure into a tight sealing position. The entire closure assembly should be inspected by the owner annually and suitably maintained to preserve its waterproof and structural quality, or be replaced as required.

7.4.3.2 FRAMES FOR OPENINGS: Each opening below the RFD shall have a metal frame suitable for providing an adequate sealing surface and for supporting the flood-proofing closure assembly. The frame shall be connected to the adjacent walls and floors and provide adequate bearing surface and anchorage to transfer the panel loading into the wall. It shall be supported upon adjacent walls and support shall be provided around the opening in the concrete or masonry wall to transfer the panel load to such intersections as required.

7.4.3.3 OPENINGS IN SHAFTS: All buildings or structures which have inclosing walls, decks, or shafts with horizontal or inclined openings at the top that are at or below the RFD and which would inundate W1 or W2 spaces shall be provided with Type 1 closure assemblies that can be readily positioned and secured to prevent entrance of flood waters. Construction of such openings shall provide for permanently affixed doors, wall extensions, gates, panels, etc., that are either hinged or on slide tracks to facilitate prompt and positive sealing or openings with only minimal manual effort. Windows, grilles, vents, door openings, etc., in the side walls of a shaft and below the RFD shall be provided with flood-proofing closures meeting the requirements of 7.4.2.

7.4.3.4 FIRE RESISTIVITY OF CLOSURE ASSEMBLIES: All flood-proofing closure assemblies shall have a fire-resistive rating that conforms to the requirements of "The Building Code" and the particular fire protection requirements for the occupancy group and building type of the structure.

7.4.4 SPECIAL APPLICATIONS OF CLOSURE ASSEMBLIES

7.4.4.1 APPLICABILITY: Residences, firms, businesses or institutions with fewer than 10 permanent employees, or spaces which are or would be unoccupied and unattended in their foreseeable normal operation for periods of greater than 72 hours, shall not have any window, doorway, or other such opening any part of which is below the RFD unless at least one of the following conditions is met: (1) Type 1 and 2 closures are utilized and are fully automatic types, (2) Manually installed closure devices meeting requirements of the appropriate flood-proofing class are provided and are installed in their protective position by the Owner at any time in the season of high flood danger during which the space will be unoccupied and unattended for periods of longer than eight (8) hours. This requirement shall be considered in the Owner's Contingency Plan and noted by the Building Official on the permit and Certificate of Occupancy. (3) Watertight exterior walls, dikes, levees, or floodwalls of adequate design (Section 7.3) are constructed to prevent flood waters up to the RFD from entering the structure or space.

SECTION 7.5 INTERNAL FLOODING AND DRAINAGE

7.5.1 SCOPE

7.5.1.1 GENERAL: The provisions of this section shall apply to the intentional flooding of buildings, structures, and spaces with water from potable or floodwater sources for the purpose of balancing internal and external pressures to protect a structure and/or its components from damage or failure during floods up to the RFD.

7.5.2 INTENTIONAL FLOODING WITH POTABLE WATER

7.5.2.1 APPLICABILITY: Spaces to be intentionally flooded (W3 spaces) to maintain a balanced internal and external pressure condition shall be filled automatically with potable water from a source provided by the Owner as required by 7.5.2.2 and approved by the Building Official. This level of filling shall be equal to that of the external flood surface unless a reduction in the internal flooding level is requested in writing by the Owner, and such approval is granted by the Building Official. The Owner shall, together with the written request, submit sufficient evidence that full internal flooding is unnecessary to protect the structure. The potable water flooding system shall activate and operate automatically and completely without human intervention and shall act independently of the emergency flooding system utilizing floodwaters as required for these spaces by 7.5.2.3. An automatic drainage system shall also be provided that will assure positive drainage of the space(s) at a rate comparable to the reduction of exterior flood height when floodwaters are receding.

7.5.2.2 POTABLE WATER SOURCES: At any location where disruption of water supply service from a public utility may occur or such service may be deemed inadequate, the Building Official shall require the Owner to provide an independent source of potable water that will be stored at the location of the improvement.

7.5.2.3 SAFEGUARD AGAINST FAILURE OF POTABLE WATER FLOODING SYSTEM: Where intentional flooding with a potable water flooding system is used for maintaining the structural integrity of buildings, structures, or spaces during flood events to the RFD, an emergency (backup) flooding system utilizing floodwaters shall be provided and maintained in a state of readiness for automatic implementation in event of failure of the primary potable water flooding system. The emergency flooding system shall comply with all requirements of 7.5.3.

7.5.3 AUTOMATIC FLOODING WITH FLOODWATER

7.5.3.1 APPLICABILITY: Spaces to be intentionally flooded with floodwater (W4) shall be provided with the necessary equipment, devices, piping, controls, etc., necessary for automatic flooding during the flood event and drainage of the space(s) when floodwaters recede. The automatic flooding and drainage system(s) shall utilize approved piping material and have sufficient capacity for raising or lowering the internal water level at a rate comparable to the anticipated rise and fall of a flood that would reach the RFD. These pipe systems shall be directly connected to the external floodwaters to maintain a balanced internal and external water pressure condition. Provisions shall be made for filling the lower portions of the structure first and for interconnections through or around all floors and partitions to prevent unbalanced filling of chambers or parts within the structures. All spaces below the RFD shall be provided with air vents extending to at least ___ feet above the elevation of the RFD to prevent the trapping of air by the rising water surface. All openings to the filling and drainage systems shall be protected by screens or grills to prevent the entry or nesting of rodents or birds in the system.

7.5.4 EMERGENCY FLOODING OF WATERPROOFED SPACES

7.5.4.1 APPLICABILITY: Spaces which have been waterproofed (W1 or W2) to the RFD shall be provided with an automatic internal flooding system meeting all requirements of 7.5.3 to maintain structural integrity during floods which exceed the RFD elevation. Inverts shall be located at the RFD elevation unless an increase in invert elevation(s) above the RFD is requested in writing by the Owner and approval is granted by the Building Official. Approvals shall not be granted by the Building Official until sufficient evidence has been furnished by the Owner that automatic internal flooding at the RFD elevation is not necessary to maintain structural integrity. Outlets for the drainage of water from waterproofed spaces shall be located properly to drain the water from all parts of the spaces. To prevent the inflow of water at flood levels below the RFD each exterior drainage outlet shall be provided with a device for preventing backflow of water (flood) through the drainage system. Auxiliary outlets shall be provided as required to evacuate all water from upper floor levels before draining the lower spaces. All watertight walls shall be designed for an internal hydrostatic pressure equal to at least two (2) feet of differential head to provide for unknown factors that may cause malfunction of the required drains.

SECTION 7.6 FLOORING

7.6.1 SCOPE

7.6.1.1 GENERAL: This section shall govern the design and use of floor systems and their constituent materials for buildings and structures located in a Flood Hazard Area.

7.6.1.2 BASIS FOR RESTRICTION: Floor systems and flooding materials are restricted according to their vulnerability to floodwater. For the purpose of these Regulations, vulnerability of a given floor or floor material may result from one or more of the following: (1) Normal suspended-floor adhesives specified for above grade use are water-soluble or are not resistant to alkali or acid in water, including ground seepage and vapor. (2) Flooring material contains wood or paper products. (3) Flooring material is not resistant to alkali or acid in water. (4) Sheet type floor coverings (linoleum, rubber, vinyl) restrict evaporation from non-W1 slabs. (5) Flooring material is impervious but dimensionally unstable.

7.6.2 FLOORING CLASSIFICATIONS

7.6.2.1 CLASSES OF FLOORING: Floor systems and flooring materials are divided into five classes according to their degree of vulnerability. Class 1 floorings require conditions of dryness provided by W1 spaces. Class 2 floors require essentially dry spaces which may be subject to water vapor and slight seepage that is characteristic of W2 spaces. Class 3 flooring may be submerged in clean water during periods of intentional flooding as provided by W3 spaces. Class 4 floorings may be exposed to and/or submerged in floodwaters in interior spaces and do not require special waterproofing protection. Class 5 floors are permitted for semi-inclosed or outside uses with essentially unmitigated flood exposure.

7.6.2.1.1 Floors of a given class may be used in any application for which a lower-numbered class is permitted by these Regulations unless specifically restricted by notation in the following chart. For example, concrete (a Class 5 floor) may be used whenever floors of Classes 1, 2, 3, 4 or 5 are permitted.

7.6.2.1.2 CLASSES OF TYPICAL FLOORING MATERIALS: The following chart is intended as an aid to the Owner, Architect/Engineer and the Building Official in assessing the vulnerability of typical materials with respect to the criteria stated in 7.6.1.2. In disputes arising over the merits of particular materials or methods of construction, the Building Official shall be guided by and decide on the basis of those criteria.

	Class
Asphalt tiles (A)	1
with asphaltic adhesives	3
Carpeting (glued-down types)	1
Cement/bituminous, formed-in-place	4
Cement/latex, formed-in-place	4
Ceramic tiles (a)	1
with acid and alkali-resistant grout	3
Chipboard	1
Clay tile	5
Concrete, precast or in situ	5
Concrete tile	5
Cork	1
Enamel felt-base floor coverings	1
Epoxy, formed-in-place	5
Linoleum	1
Magnesite (magnesium oxychloride)	1
Mastic felt-base floor coverings	1
Mastic flooring, formed-in-place	5
Polyurethane, formed-in-place	5
PVA emulsion cement	1
Rubber sheets (A)	1
with chemical-set adhesives (B)	5*
Rubber tiles (A)	1
with chemical-set adhesives (B)	4
Silicone floors, formed-in-place	5
Terrazzo	4
Vinyl sheets (homogenous) (A)	1
with chemical-set adhesives (B)	5*
Vinyl tile (homogeneous) (A)	1
with chemical-set adhesives (B)	4
Vinyl tile or sheets (coated on cork or wood product backings)	1
Vinyl-asbestos tiles (semi-flexible vinyl) (A)	1
with asphaltic adhesives	4
Wood flooring or underlayments	1
Wood composition blocks, laid in cement mortar	2
Wood composition blocks, dipped and laid in hot pitch or bitumen	2

* Not permitted as Class 2 flooring

Notes: (A) Using normally-specified suspended floor (i.e., above-grade) adhesives, including sulfite liquor (lignin or "linoleum paste"), rubber/Asphaltic dispersions, or "alcohol" type resinous adhesives (cumar, oleoresin).

(B) e.g., epoxy-polyamide adhesives or latex-hydraulic cement.

SECTION 7.7 WALLS AND CEILINGS

7.7.1 SCOPE

7.7.1.1 GENERAL: This section shall govern the design and use of wall and ceiling systems and their constituent materials for buildings and structures located in a Flood Hazard Area.

7.7.1.2 BASIS FOR RESTRICTION: Materials treated in this section are those which constitute interior walls and ceilings including their finishes and structural constructions upon which they depend such as sheathing and insulation, and are restricted according to their susceptibility to flood damage. For the purpose of these Regulations, susceptibility of a given interior material or construction is dependent on one or more of the following: (1) Normal adhesives specified for above-grade use are water-soluble or are not resistant to alkali or acid in water, including ground seepage and vapor. (2) Wall or ceiling material contains wood, wood products, gypsum products, or other material which dissolves or deteriorates, loses structural integrity, or is adversely affected by water. (3) Wall or ceiling material is not resistant to alkali or acid in water. (4) Material is impervious but dimensionally unstable. (5) Materials absorb or retain water excessively after submergence.

7.7.2 WALL/CEILING CLASSIFICATIONS

7.7.2.1 CLASSES OF WALL/CEILING: Wall and ceiling systems and materials are divided into five classes according to the degree of vulnerability. Class 1 materials require conditions of dryness provided by W1 spaces. Class 2 materials require essentially dry spaces which may be subject to water vapor and slight seepage that is characteristic of W2 spaces. Class 3 wall and ceiling materials may be submerged in clean water during periods of intentional flooding as provided by W3 spaces. Class 4 materials may be exposed to and/or submerged in flood waters in interior spaces and do not require special waterproofing treatments or protection. Class 5 wall and ceiling materials are permitted for semi-inclosed or outside uses with essentially unmitigated flood exposure.

7.7.2.1.1 Materials of a given class may be used in any application for which a lower-numbered class is permitted by these Regulations. For example, concrete (a Class 5 wall/ceiling material) may be used whenever materials of Classes 1, 2, 3, 4 or 5 are permitted.

7.7.2.2 CLASSES OF TYPICAL WALL/CEILING MATERIALS: The following chart is intended as an aid to the Owner, Architect/ Engineer and the Building Official in assessing the vulnerability of typical materials with respect to the criteria stated in 7.7.1.2. In disputes arising over the merits of particular products or of materials not listed below, the Building Official shall be guided by and decide on the basis of those criteria.

	Class
Asbestos-cement board	5
Brick, face or glazed	5
Common	2
Cabinets, built in	
Wood	2
Metal	5
Cast stone (in waterproof mortar)	5
Calkboards	
Slate, porcelain glass, lucite glass	5
Cement-asbestos	2
Composition, painted	2
Chipboard	1
Exterior Sheathing Grade	2
Clay tile	
Structural glazed	5
Ceramic veneer, ceramic wall tile-mortar set	4
Ceramic veneer, organic adhesives	2
Concrete	5
Concrete block	5
Corkboard	2
Doors	
Wood, hollow	2
Wood, lightweight panel construction	2
Wood, solid	2
Metal, hollow	5
Metal, Kalamein	2
Fiberboard panels, Vegetable types	
Sheathing grade (asphalt-coated or -impregnated)	2
Other	1
Gypsum products	
Gypsum board	2
Keene's cement on plaster	2
Plaster, otherwise, including acoustical	2
Sheathing panels, exterior grade	2
Glass (sheets, colored tiles, panels)	4
Glass blocks	5
Hardboard	
Tempered, enamel or plastic-coated	2
All other types	2

	Class
Insulation	
Foam or closed cell types	4
Batt or blanket types	1
All other types	2
Metals, non-ferrous (aluminum, copper or zinc tiles)	3
Ferrous	5
Mineral fiberboard	1
Plastic wall tiles (polystyrene, urea formaldehyde, etc.) with waterproof adhesives, painted with waterproof grout	3
Set in water-soluble adhesives	2
Paint	
Polyester-epoxy and other waterproof types	4
All other types	1
Paperboard	1
Partitions, folding	
Metal	4
Wood	2
Fabric-covered types	1
Partitions, stationary	
Wood frame	4
Metal	5
Glass, unreinforced	4
reinforced	4
Gypsum, solid or block	1
Rubber, mouldings and trim with epoxy-polyamide adhesive or latex-hydraulic cement	4
All other applications	1
Steel, (panels, trim, tile) with waterproof applications	5
With non-waterproof adhesives	2
Stone, natural solid or veneer, waterproof grout	5
Stone, artificial nonabsorbent solid or veneer, waterproof grout	5
All other applications	2
Strawboard	
Exterior grade (asphalt-impregnated kraft paper)	2
All other types	1
Wall coverings	
Paper, burlap, cloth types	1
Wood	
Solid (boards, sheets, or trim)	2
Plywood	
Exterior grade	2
Otherwise	1

SECTION 7.8 ELECTRICAL

7.8.1 SCOPE

7.8.1.1 GENERAL: Where buildings or parts of buildings and structures extend below the RFD, the electrical materials, equipment and installation shall conform to the requirements of this section of the Regulations.

7.8.2 REQUIREMENTS AT LOCATIONS ABOVE AND BELOW THE RFD

7.8.2.1 MAIN POWER SERVICE: The incoming main commercial power service equipment, including all metering equipment, shall be located above the RFD. Whenever a building or structure is not accessible by a bridge, walkway or other connecting means except by boat during periods of flooding to the RFD, a disconnecting means for the incoming main commercial power service shall be provided at an accessible remote location above the RFD.

7.8.2.2 STATIONARY AND PORTABLE EQUIPMENT: Switchgear, control centers, transformers, distribution and main lighting panels in addition to all other stationary equipment shall be located above the RFD. Portable or movable electrical equipment may be located in any space below the RFD provided that equipment can be disconnected by a single plug and socket assembly of the submersible type and rated by the manufacturer as submersible for not less than 72 hours for the head of water above the assembly to the RFD. All disconnect assemblies shall be provided with submersible seals attached to the disconnect assembly by means of a corrosion resistant metal chain for immediate use when needed to insure safety to all personnel during a flood. All portable or movable equipment should be de-energized and/or moved out of potentially flooded spaces at time of flood warning and prior to floodwaters reaching floor levels where such equipment is located.

7.8.2.3 NORMAL AND EMERGENCY LIGHTING CIRCUITS: All circuits, except emergency lighting circuits, extending into areas below the RFD shall be energized from a common distribution panel located above the RFD. All emergency lighting circuits into areas below the RFD shall be energized from an independent distribution panel also located above the RFD. Each distribution panel shall have the capability of being de-energized by a separate single disconnecting device.

7.8.2.4 EMERGENCY LIGHTING REQUIREMENTS: All areas of the building or structure that are below the RFD, where personnel may be required to conduct emergency operations or work with water present on the floor of the area during a flood, shall be provided with automatically operated emergency lighting facilities and automatically operated electrical disconnect equipment to insure that all electrical circuits into these areas, except emergency lighting circuits, are de-energized prior to personnel working in water. The electrical circuits shall be de-energized prior to the presence of any water on the floor of the affected area. All components of emergency lighting systems installed below the RFD shall be so located that no component of the emergency lighting system is within reach of personnel working at floor level in the areas where emergency lighting systems are utilized unless the emergency lighting circuits are provided with ground-fault circuit interrupters having a maximum leakage current to ground sensitivity of five (5) milliamperes. The energy for emergency lighting may be furnished by a storage battery(s), prime mover-generator system, a separate commercial power supply system, the same commercial power system, or a combination thereof, subject to the following provisions of this section.

7.8.2.4.1 STORAGE BATTERY (including battery-operated lighting units): Battery-operated lighting units shall be completely self-contained and shall indicate the state of charge of the battery at all times. Lighting units shall automatically provide light when the normal source of lighting in the areas is de-energized. A sufficient number of emergency lighting units shall be provided to enable personnel to perform their assigned emergency tasks and to permit a safe exit to areas above the RFD.

7.8.2.4.2 SEPARATE COMMERCIAL POWER SUPPLY SYSTEM: This source of energy shall have a degree of reliability satisfactory to the Building Official. A system fed from a substation other than that used for the regular supply and not on the same poles (except service pole) as the regular supply is deemed to have the required degree of reliability. A secondary circuit fed from the same primary network circuit as the regular supply shall be regarded as a separate system.

7.8.2.4.3 SAME COMMERCIAL POWER SUPPLY SYSTEM: The system shall be an underground secondary network system and a separate service shall be connected on the line side of the service switch or breaker of the regular service.

7.8.2.5 LIGHTING CIRCUITS BELOW REGULATORY FLOOD DATUM: Lighting circuit switches, receptacles and lighting fixtures operating at a maximum voltage of 120 volts to ground may be installed below the RFD, provided that these circuits shall be de-energized as noted in 7.8.2.4. Should any switch, receptacle or lighting fixture be flooded, its particular circuit shall not be re-energized until such circuits and devices and/or any part thereof, have been disassembled and thoroughly checked, cleaned or replaced, and approved for use by qualified personnel.

7.8.2.6 SUBMERSIBLE EQUIPMENT: Except for the switches, receptacles and lighting fixtures noted herein, all other electrical equipment permanently installed below the RFD shall be of the submersible type rated by the manufacturer for submergence for not less than 72 hours for a head of water above equipment to the RFD.

7.8.2.7 SUBMERSIBLE WIRING REQUIREMENTS: All electrical wiring systems installed below the RFD shall be suitable for continuous submergence in water and shall contain no fibrous components. Only submersible type splices will be permitted in areas below the RFD. All conduits located below the RFD shall be so installed that they will be self-draining if subject to flooding conditions.

7.8.2.8 ELEVATORS: All electric power equipment and components of elevator systems shall be located above the RFD. Automatic type elevators shall be provided with a home station to which the elevator will automatically return after use, with home station located above the RFD.

7.8.2.9 ELECTRIC HEATING EQUIPMENT: Electric unit heaters installed below the RFD shall be capable of disconnection and removal in the manner described for portable electrical equipment in 7.8.2.2. Electric controls on gas and oil furnaces located below the RFD shall not exceed 120 volts to ground and the control circuits shall be automatically de-energized prior to the presence of any water on the floor of the affected area in accordance with 7.8.2.4.

7.8.2.10 SUMP PUMP INSTALLATION: Buildings and structures utilizing sump-pumping equipment of any type to keep areas within the structure free of water shall be provided with float-operated warning alarms that shall act independently of any other float-actuated devices used to start and stop pumping equipment. All buildings or structures utilizing sump-pumping equipment shall be provided with automatic starting standby electrical generating equipment located above the RFD. The standby generating equipment shall be capable of remaining in continuous operation for a period of 125% of the anticipated duration of the design flood.

SECTION 7.9 MECHANICAL

7.9.1 SCOPE

7.9.1.1 GENERAL: All mechanical systems, including heating, air conditioning, ventilating, plumbing, sanitary, and water systems, in or serving buildings or structures in a Flood Hazard Area, shall be designed and installed to comply with the requirements of this section.

7.9.2 HEATING, AIR CONDITIONING AND VENTILATION SYSTEMS

7.9.2.1 APPLICABILITY: Heating, air conditioning, and ventilation systems, including all appurtenances, in buildings or structures in a Flood Hazard Area shall be designed and installed to comply with the requirements of these Regulations.

7.9.2.2 LOCATION: Heating, air conditioning, and ventilating Equipment should, to the maximum extent possible, be installed in areas and spaces of buildings that are above the RFD. When not feasible, said equipment shall be located in W1 or W2 spaces (below the RFD) with direct access provided from a location above the RFD and shall conform to all requirements of this Section.

7.9.2.2.1 Heating systems utilizing gas- or oil-fired furnaces shall have a float operated automatic control valve installed in the fuel supply line which shall be set to operate when floodwaters reach an elevation equal to the floor level of the space where furnace equipment is installed. A manually operated gate valve that can be operated from a location above the RFD shall be provided in the fuel supply line to serve as a supplementary safety provision for fuel cutoff. The heating equipment and fuel storage tanks shall be mounted on and securely anchored to a foundation pad or pads of sufficient mass to overcome buoyancy and prevent movement that could damage the fuel supply line. As an alternate means of protection, elevation of heating equipment and fuel storage tanks above the RFD on platforms or by suspension from overhead structural systems will be permitted. All unfired pressure vessels will be accorded similar treatment. Fuel lines shall be attached to furnaces by means of flexible or swing-type couplings. All heating equipment and fuel storage tanks shall be vented to an elevation of at least 3 feet above the RFD. Air supply for combustion shall be furnished if required for systems installed in W1 or W2 spaces, and piping or duct work for such purpose shall be terminated at least 3 feet above the RFD.

7.9.2.2.1.1 All duct work for warm air heating systems which is located below the RFD shall be provided with emergency openings for internal flooding and drainage of the ducts with all openings having covers with gravity operators for closure during normal operation. Where duct work must pass through a watertight wall or floor below the RFD, the duct work shall be protected by a mechanically operated closure assembly and shall be provided with the operator control position above the RFD. The closure assembly in its open position shall not impede the normal function of the heating system.

7.9.2.2.1.2 Steam or hot water heating pipes located below the RFD shall be provided with shutoff valves sufficient to isolate the piping system when warning of flooding to the RFD is received.

7.9.2.2.1.3 Electric heating systems, where utilized in Flood Hazard Areas, shall be installed in accordance with requirements of Section 7.8.

7.9.2.2.2 Air conditioning and ventilation systems that will be located below the RFD shall be installed in W1 or W2 spaces only. All installation, piping, duct work, connections, and safety features shall conform to the same requirements stated for Heating Systems in paragraph 7.9.2.2.1.

7.9.2.2.3 Where heating, air conditioning, or ventilating systems (as defined in 7.9.2.2) are installed in other than W1 or W2 spaces, all bearings, seals, shafts, gears, clutches, valves, or controls which are not capable of withstanding water or silt damage or hydrostatic or hydrodynamic loading shall be provided with suitable protective waterproofing enclosures as may be required by the Building Official, unless they are considered expendable.

7.9.2.2.4 All fuel supply lines that originate either outside of W1 or W2 spaces or pass through areas that would be flooded shall be equipped with automatic shutoff valves to prevent loss of fuel in the event of a line breakage. The wall opening shall be made flood-proof by use of imbedded collars, sleeves, waterstops, or other means as may be approved by the Building Official.

7.9.2.2.5 Electrical connections to all mechanical systems covered by this section shall conform to the requirements of Section 7.8.

7.9.3 PLUMBING SYSTEMS

7.9.3.1 APPLICABILITY: For the purpose of the Regulations, plumbing systems shall include sanitary and storm drainage, sanitary facilities, water supply, storm water and sewage disposal systems.

7.9.3.1.1 Except as otherwise provided herein, nothing in these Regulations shall require the removal, alteration, or abandonment of, nor prevent the continued use of, an existing plumbing system.

7.9.3.1.2 No plumbing work shall be commenced until a permit for such work has been issued by the Building Official. Application for plumbing permits, denial of permit, time limitation on permits, and inspections shall be in accordance with requirements of the Building Code.

7.9.3.1.3 Plumbing materials shall be selected with due consideration given to the hydrostatic, hydrodynamic and chemical actions of floodwaters on the interior of piping systems, of the soil, fill or other materials on the exterior of piping systems, on joints, connections, valves, traps, seals (and caulking), and fixtures.

7.9.3.2 BELOW RFD: Sanitary sewer and storm drainage systems that have openings below the RFD shall be provided with automatic backwater valves or other automatic backflow devices that are installed in each discharge line passing through a building exterior wall. In W1 spaces, manually operated shutoff valves that can be operated from a location above the RFD shall also be installed in such lines to serve as supplementary safety provisions for preventing backflow in case of automatic backflow device failure or line break between the space(s) and the device.

7.9.3.2.1 Spaces in buildings that are to be protected from floodwaters by implementation of the Owner's Contingency Plan may utilize standpipes attached to floor drains, cleanouts, and other openings below the RFD, and/or manually operated shutoff valves or closure devices.

7.9.3.2.2 Where the state of dryness of a space is dependent on a sump pump system, or where the stability of a structure during a flood event depends on the relief of uplift pressures on building components, all interior storm water drainage or seepage, appliance drainage, and underslab drain tile systems shall be directly connected to a sump (pump) and discharged at an elevation at least 2 feet above the RFD.

7.9.3.2.3 Sanitary sewer systems, including septic systems, that are required to remain in operation during a flood shall be provided with a sealed holding tank and the necessary isolation and diversion piping, pumps, ejectors and appurtenances required to prevent sewage discharge during the flood. The holding tank shall be sized for storage of at least 150% of the anticipated demand for the duration of a flood to the RFD.

7.9.3.2.3.1 All vents shall extend to an elevation of at least 3 feet above the RFD.

7.9.3.2.3.2 All pipe openings through walls below the RFD shall be flood-proofed to prevent floodwater backflow through spaces between pipes and wall construction materials. (See 7.9.2.2.4.)

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CHAPTER 8

WIND

SECTION 8.1 GENERAL: Buildings and structures and every part thereof shall be designed to withstand the forces of wind pressure assumed in any direction. No allowance shall be made for the effect of shielding by other structures. As further described in these Regulations, the floor, roof or other horizontal bracing system shall be designed and constructed to transfer horizontal forces to the parts of the structural frame designed to carry the forces to the ground. Where horizontal or vertical shear-resisting elements are used to transfer wind forces through diaphragm action, the analysis shall include the design of chord members at or near the extremities of the diaphragm and the connections used to transfer the forces to the resisting elements. The total shear in any horizontal plane shall be distributed to the various elements of the lateral force-resisting system in proportion to their rigidities, taking into consideration the rigidity of the horizontal bracing system or diaphragm. Where roofs or floors are constructed of individual units and the transfer of forces to the building frame or foundation is totally or partially dependent on such units, the unit and attachment shall be capable of resisting applied loads in both vertical and horizontal directions.

SECTION 8.2 VELOCITY PRESSURES:

8.2.1 WIND SPEED: The basic wind speeds to be used in design of buildings and structures shall be as follows:

Hazard Zone	Basic Wind Speed in MPH at 30 Feet Above Ground
A	140
B	140
C	140
D	140 at C-D boundary,

diminishing to 100 mph at inland boundary in accordance with the following:

$$V_D = 100 + \frac{40}{1+d^2}, \text{ where } V_D = \text{wind speed in Zone D}$$

$$d = \text{distance inland from C-D boundary}$$

8.2.2 VELOCITY PRESSURES FOR ORDINARY BUILDINGS AND STRUCTURES: Velocity pressures for ordinary buildings and structures are given in Table 8-1. These velocity pressures are to be multiplied by the pressure coefficients as described in 8.3. The effective velocity pressures take into account the dynamic response to gusts

TABLE 8-1

Effective Velocity Pressure
for Ordinary Buildings and Structures
in Pounds Per Square Foot

Elevation	Wind Speed 100	110	120	130	140
Less than 30'	26	32	39	45	52
30 - 40	33	40	48	56	65
40 - 75	38	46	54	64	74
75 - 125	44	53	63	74	86
125 - 175	48	58	69	81	94
175 - 225	51	62	74	86	100
225 - 275	53	65	77	90	104
275 - 325	56	68	80	94	109
325 - 375	58	70	83	97	112
375 - 425	59	72	86	100	116
425 - 475	61	74	88	103	119
475 - 525	62	75	90	105	122
525 - 575	64	77	92	108	125
575 - 625	65	79	94	110	128
625 - 675	66	80	96	112	130
675 - 725	67	82	97	114	132
725 - 775	68	83	99	116	135
775 - 800	70	85	101	118	137

To find wind pressure at speed not shown in Table:

$$P_{V_n} = \frac{P_V V_n^2}{V^2}$$

where P_{V_n} = pressure not shown in Table

V_n = velocity not shown in Table

P_V = pressure shown in Table

V_n = velocity corresponding to P_V

of ordinary buildings and structures in a direction parallel to the wind and should be considered as a minimum. They do not provide for the effects of vortex shedding or instability due to galloping or flutter. For buildings whose height exceeds five times the least horizontal dimension, and for buildings whose dynamic properties tend to make them wind-sensitive, a detailed analysis shall be required.

8.2.3 VELOCITY PRESSURES FOR PARTS AND PORTIONS: For parts and portions of structures, such as girts, purlins, windows, doors, curtain walls and cladding, etc., and tributary areas less than 200 sq. ft., the velocity pressures given in Table 8-2 shall be used. These values shall be multiplied by the pressure coefficients described in Tables 8-4, 8-5, or 8-6 and 8-7. For tributary areas from 200 to 1000 sq. ft., the values may be reduced linearly to the values in Table 8-1.

8.2.4 INTERNAL VELOCITY PRESSURES: Internal velocity pressures are given in Table 8-3. These are to be used with internal pressure coefficients listed in Table 8-8. The pressure is assumed to be uniform on all internal surfaces at a given building height.

SECTION 8.3 PRESSURE COEFFICIENTS:

8.3.1 GENERAL: In the following sections, pressure coefficients are given for various building shapes and for various building element locations and configurations. These coefficients are to be multiplied by the appropriate velocity pressures given in Section 8.2. (Unit wind load = velocity pressure x pressure coefficient.) In the calculation of design wind loads on buildings and structures or elements thereof, the pressure difference between opposite faces shall be taken into account. Where more than one coefficient is specified, each shall be considered in determining the maximum stresses. The total design wind load on a building or structure may be obtained by calculating the vector sum of the resultant forces that act on its elements.

SECTION 8.4 DESIGN OF BUILDINGS AND OTHER ENCLOSED STRUCTURES:

8.4.1 GENERAL: All buildings and other enclosed structures shall be designed to withstand the sliding and overturning effects of wind, allowing for the wind that is normal to any wall. The pressure distributions shall be determined by employing the appropriate pressure coefficients specified below.

8.4.2 PRESSURE COEFFICIENTS: The pressure coefficients given in this section apply to typical rectangular buildings and other enclosed structures that have vertical walls which may have doors, openable windows, etc. The positive and negative coefficients indicate positive pressure and suction pressure, respectively.

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TABLE 8-2

Effective Velocity Pressure for Parts and
Portions of Buildings and Structures
in Pounds Per Square Foot

Elevation	Wind Speed 100	110	120	130	140
Less than 30'	38	46	55	64	74
30 - 75	42	51	61	72	84
75 - 125	49	59	70	82	95
125 - 175	53	65	77	90	104
175 - 225	57	69	82	96	111
225 - 275	59	72	86	101	117
275 - 325	61	74	88	104	121
325 - 375	64	77	92	108	125
375 - 425	66	80	95	111	129
425 - 475	67	81	96	113	131
475 - 525	69	84	99	117	136
525 - 575	70	85	101	119	138
575 - 625	72	87	104	122	142
625 - 675	72	88	104	123	143
675 - 725	74	90	107	126	146
725 - 775	76	91	109	128	148
775 - 800	76	92	110	129	150

TABLE 8-3

Effective Velocity Pressures for Calculating Internal Pressures in Pounds Per Square Foot

Height	Wind Speed 100	110	120	130	140
Less than 30'	26	31	37	43	50
30 - 75	30	36	43	50	58
75 - 125	36	44	52	61	71
125 - 175	40	49	58	68	79
175 - 225	44	53	63	74	86
225 - 275	47	57	67	79	92
275 - 325	49	60	71	83	96
325 - 375	51	62	74	87	101
375 - 425	54	65	77	90	104
425 - 475	55	67	80	93	108
475 - 525	57	69	82	96	111
525 - 575	59	71	84	99	115
575 - 625	60	73	87	102	118
625 - 675	61	74	88	104	121
675 - 725	63	76	91	106	123
725 - 775	64	77	92	108	125
775 - 800	65	79	94	110	128

TABLE 8-4

External Pressure Coefficients
for Walls

Location of Wall	Pressure Coefficient
Windward wall	0.8
Leeward wall, both height-width and height-length ratios of building ≥ 2.5	-0.6
Other buildings	-0.5
Side walls	-0.7

TABLE 8-5

External Pressure Coefficient for
Arched Roofs

	Rise to Span Ratio	Windward Quarter	Center Half	Leeward Quarter
Roof on elevated structure	0 < r < 0.2	-0.9	(-0.7 - r)	-0.5
	0.2 < r < 0.3	(1.5r - 0.3)*	(-0.7 - r)	-0.5
	0.3 < r < 0.6	(2.75r - 0.68)	(-0.7 - r)	-0.5
Roof springing from ground level	0 < r < 0.6	1.42r	(-0.7 - r)	-0.5

* *When the rise-span ratio is (0.2 < r 0.3), alternate coefficients given by (6r - 2.1) shall also be used for the windward quarter.*

TABLE 8-6

External Pressure Coefficients for Windward Slope of Gabled Roofs

	θ								
h/w	10°-15°	20°	25°	30°	35°	40°	45°	50°	60°
≤ 0.3	0.01 θ*	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.01 θ
0.5	-1.0	-0.75	-0.5	-0.2	0.05	0.3	0.45	0.5	0.01 θ
1.0	-1.0	-1.0	-0.8	-0.55	-0.3	-0.05	0.2	0.45	0.01 θ
≥ 1.5	-1.0	-1.0	-1.0	-0.9	-0.6	-0.35	-0.1	0.2	0.01 θ

* *Except for roofs rising from ground level (h/w = U), a coefficient of -1.0 shall be used when 10° ≤ θ ≤ 15°, θ = slope in degree, from horizontal, h = wall height at eave, w = least width of building normal to ridge.*

TABLE 8-7

Local Peak External Pressure Coefficients for Roofs

Roof Slope θ, Degrees*	Ridges and Eaves	Corners
0 - 30	-2.4	(0.1 θ - 5.0)
Greater than 30	-1.7	-2.0

* *For arched roofs, θ shall be taken as the angle between the horizontal and the tangent to the roof at the springing.*

TABLE 8-8

Internal Pressure Coefficients for Buildings

n*	Openings Uniformly Distributed	Openings Mainly In = Windward Wall	Leeward Wall	Side Wall(s)
0 to 0.3	± 0.3	(0.3 + 1.67n)	(-0.3 - n)	(-0.3 - n)
Greater than 0.3	± 0.3	0.8	-0.6	-0.6

* *n = ratio of open area to solid area of wall having majority of openings*

8.4.3 EXTERNAL PRESSURE COEFFICIENTS: The average pressure coefficients, listed in Table 8-4, shall be used for calculating pressures on external surfaces of buildings.

8.4.3.1 WALLS - LOCAL PRESSURE COEFFICIENTS: A pressure coefficient of -2.0 shall be used at the corners of all walls. The pressure shall be assumed to act on vertical strips of width 0.1 w, where w is the least width of the building, and the computed pressure shall be applied outward. These local pressures shall not be included with the net external pressure when computing overall loads.

8.4.3.2 ROOFS:

8.4.3.2.1 GENERAL: For buildings with a ratio of wall height to least width less than 2.5, an external suction coefficient of -0.7 shall be used for the roof and the computed pressure shall be assumed uniform over the entire roof area. For buildings in which the height-width ratio is 2.5 or greater, a value of -0.8 shall be used for the entire roof area. These coefficients allow for wind parallel to the surfaces of flat, arched, and sloped roofs.

8.4.3.2.2 ARCHED ROOFS: For wind perpendicular to the axis of the arch, the coefficients of Table 8-5 shall be used.

8.4.3.2.3 GABLED ROOFS: For wind perpendicular to the ridge of gabled roofs, a pressure coefficient of -0.7 shall be used for the leeward slope, together with a coefficient for the windward slope which depends on the roof slope and the height-width ratio of the building, as given in Table 8-6. These coefficients may also be used for shed and other sloped roofs of buildings.

8.4.3.2.4 LOCAL PRESSURE COEFFICIENTS: The pressure coefficients given in Table 8-7 shall be used at the ridges, eaves, cornices and 90-degree corners of roofs. The pressure shall be assumed to act on strips of 0.1 w and the computed pressure applied outward at these locations along the ridge, eaves and cornices; w = least width of building normal to ridge. These local pressures shall not be included with the net external pressure when computing overall loads.

8.4.3.2.5 OTHER LIVE LOADS ON ROOFS: In no case shall any roof be designed for less than 20 pounds per square foot live load.

8.4.4 INTERNAL PRESSURE COEFFICIENTS: Pressure acting on the interior surfaces of walls and roofs of buildings shall be computed by multiplying the velocity pressure obtained from Table 8-3 by the internal pressure coefficient obtained in Table 8-8.

Both positive and negative coeffients shall be considered in calculating the maximum stresses.

SECTION 8.5 ROOFS OVER NON-ENCLOSED STRUCTURES:

8.5.1 NET PRESSURE COEFFICIENTS: The net pressure coefficients for horizontal or inclined flat roofs over non-enclosed structures, such as open-air parking garages, shelter areas, outdoor arenas, stadium and theaters, shall be as given in Table 8-9 in which "a" is the angle between the wind direction and the plane of the roof and "λ" is the ratio of the length of the windward edge to the distance between the windward and the leeward edges (aspect ratio).

8.5.2 INWARD AND OUTWARD LOADS: The net pressure coefficients given in Table 8-9 are to be used in computing the resultant load normal to the surface. The resultant load may act either inward or outward.

8.5.3 ANGLE OF ATTACK: In computing the angle between the wind direction and the plane of the roof, the wind shall be assumed to deviate by plus or minus 10 degrees from the horizontal.

8.5.4 VARIATION OF PRESSURE: Pressures will be higher at the windward edge than at the leeward edge. To allow for this difference, the resultant load shall be assumed to act at the center of pressure X/C, as given in Table 8-10, where X is the distance to the center of pressure from the windward edge of the roof and C is the distance between the windward and leeward edges.

SECTION 8.6 CHIMNEYS, TANKS, AND SIMILAR STRUCTURES: Net pressure coefficients for chimneys, tanks, and similar structures shall be as given in Table 8-11. These coefficients apply to the projected area of the structure on a vertical plane normal to the wind direction. For slender structures such as flagpoles, a minimum net pressure coefficient shall be used if $d\sqrt{q} < 2.5$.

SECTION 8.7 SIGNS AND OUTDOOR DISPLAY STRUCTURES:

8.7.1 GENERAL: For the purpose of determining wind loads, all signs shall be classified as either open or solid. Signs with openings greater than 30% of the gross area shall be classified as "open" signs. Those with openings less than 30% of the gross area shall be classified as "solid" signs. The effective velocity pressures of Table 8-2 shall be used in calculating design loads.

8.7.2 SOLID SIGNS:

8.7.2.1 HEIGHT ABOVE GROUND: Solid signs are classified as being at the ground when the ratio g/h is less than 0.25; otherwise, they are classified as being above ground (g = distance between the bottom of the sign and the ground, and h = the vertical dimension of the sign).

TABLE 8-9

Net Pressure Coefficients for Flat Plates

a	λ						
	1/5	1/3	1/2	1	2	3	5
10°	0.2	0.25	0.3	0.45	0.55	0.70	0.75
15°	0.35	0.45	0.5	0.68	0.83	0.88	0.83
20°	0.5	0.6	0.75	0.92	1.0	0.96	0.9
25°	0.7	0.8	0.95	1.14	1.1	1.04	0.95
30°	0.9	1.0	1.2	1.32	1.2	1.1	1.0

TABLE 8-10

Location of Center of Pressure, X/C, for Flat Plates

a	λ		
	1/5 to 1/2	1	2-5
10°	0.35	0.30	0.30
15°	0.35	0.30	0.30
20°	0.35	0.32	0.32
25°	0.35	0.36	0.40
30°	0.35	0.30	0.45

TABLE 8-11

Net Pressure Coefficients for
Chimneys and Tanks

Shape	Type of Surface	h/d		
		1	7	25
Square (wind normal to a face)	Smooth or rough	1.3	1.4	2.0
Square (wind along diagonal)	Smooth or rough	1.0	1.1	1.5
Hexagonal or octagonal ($d\sqrt{q} > 2.5$)	Smooth or rough	1.0	1.2	1.4
Round ($d\sqrt{q} > 2.5$)	Moderately smooth Rough ($d'/d \cong 0.02$) Very Rough ($d'/d \cong 0.08$)	0.5 0.7 0.8	0.6 0.8 1.0	0.7 0.9 1.2

NOTE: h = height of structure in feet
d = diameter or least horizontal dimension in feet
d'= depth in feet of protruding elements such as ribs and spoilers
q = the effective velocity pressure in psf from Table 8-1

8.7.2.2 NET PRESSURE COEFFICIENTS:

8.7.2.2.1 NORMAL WIND INCIDENCE: The net pressure coefficients, C_f, for solid signs at ground level and above ground level, for wind normal to the surface, shall be as given in Table 8-12 in which H is the height-to-width ratio of the surface, a is the greater dimension, and b is the smaller dimension. The computed load shall be assumed to act uniformly over the entire sign area.

8.7.2.2.2 OBLIQUE WIND INCIDENCE: To allow for winds oblique to the surfaces of solid signs, the net pressure normal to the surfaces shall be assumed to vary linearly from a maximum of the windward edge to a minimum of the leeward edge, in accordance with the following equations:

$$\text{Max } C_f = 1.6\ K\ C_f$$
$$\text{Min } C_f = 0.4\ K\ C_f$$

where C_f is the net pressure coefficient for normal incidence, and K is a factor depending upon the orientation of the sign relative to the wind. The values of K for signs at, and above, ground level shall be as follows: K = 1.0 for rectangular signs having the shorter edge upwind; K = 1.15 for rectangular signs having the longer edge upwind and for square signs.

8.7.3 OPEN SIGNS: For open signs the net pressure coefficients given in Table 8-13 shall be applied to the projected area normal to the wind of all exposed members and elements (excluding appurtenances and supports which shall be accounted for separately by using the appropriate net pressure coefficients for these individual elements). Table 8-13 gives net pressure coefficients for lattices that are comprised of flat-sided or rounded elements, where ϕ is the ratio of the solid area to the gross area, d is the diameter in feet of a typical element, and "q" is the velocity pressure in psf. Weighted average coefficients may be used for signs with both flat-sided and rounded elements.

8.7.4 APPURTENANCES AND SUPPORTS: The wind loading on appurtenances and supports shall be accounted for separately by using the appropriate net pressure coefficients. Allowances may be made for the shielding effect of one element or another.

SECTION 8.8 SQUARE - AND TRIANGULAR - SECTION TRUSSED TOWERS:

8.8.1 TOWERS WITH FLAT-SIDED MEMBERS: The net pressure coefficients to be applied to Table 8-1 for square- and triangular-section towers with similar faces comprised of structural angle or similar flat-sided members, and with the wind normal to a face, shall be as given in Table 8-14. Here, ϕ is the ratio of the solid area to the gross area of the face and the net pressure coefficient applies to the solid area of the face. For square towers, the

TABLE 8-12

Net Pressure Coefficients for Signs
At and Above Ground Level, C_f

At Ground Level							
H	≤ 3	5	8	10	20	30	≥ 40
C_f	1.2	1.3	1.42	1.52	1.75	1.84	2.0

Above Ground Level							
a/b	≤ 6	10	16	20	40	60	≥ 80
C_f	1.2	1.3	1.42	1.52	1.75	1.84	2.0

TABLE 8-13

Net Pressure Coefficients for
Latticed Frameworks, C_f

ϕ	Flat-Sided Members	Rounded Members	
		$d\sqrt{q} < 2.5$	$d\sqrt{q} > 2.5$
Less than 0.1	2.0	1.2	0.8
0.1 to 0.3	1.8	1.3	0.9
0.3 to 0.7	1.6	1.5	1.1

coefficients do not allow for any unmasked (outstanding) lacing on the side faces; such lacing shall be accounted for separately by using the appropriate net pressure coefficients for these elements and by neglecting the interference effects of the other parts of the tower.

8.8.2 TOWERS WITH ROUNDED MEMBERS: For square- and triangular-section towers with round members, and with wind normal to a face, the net pressure coefficients shall be determined by multiplying the above coefficients for towers with flat-sided members by the factors in Table 8-15 for corresponding values of ϕ. Weighted average coefficients may be used for towers with both flat-sided and rounded members.

8.8.3 OBLIQUE WIND INCIDENCE:

8.8.3.1 SQUARE-SECTION TOWERS: To allow for the maximum horizontal wind-load on square-section trussed towers, which occurs when the wind is oblique to the faces, the wind for normal wind incidence shall be multiplied by a factor of $(1.0 + 0.75\ \phi)$ (for $\phi < 0.5$) and shall be assumed as acting along a diagonal.

8.8.3.2 TRIANGULAR-SECTION TOWERS: For oblique incidence, the wind force on triangular-section trussed towers (although lower than for normal wind incidence) shall be assumed to be the same as for normal incidence.

8.8.4 TOWER APPURTENANCES: The wind-loading on tower appurtenances, such as ladders, conduits, lights, elevators, etc., shall be as calculated by using the appropriate net pressure coefficient for these elements and the effective velocity pressures of Table 8-2. The contribution of these elements to the tower wind-loading shall be based on the effective velocity pressures of Table 8-2. Allowance may be made for shielding effects.

8.8.5 TOWER GUYS: The minimum net pressure coefficient for wind normal to the chord of tower guys shall be 1.2. For oblique wind incidence, the net pressure coefficients shall be as given in Table 8-16 in which B is the angle between the wind direction and the chord of the guy, C_D is the drag coefficient which defines the horizontal component of the wind forces in the direction of the wind, and C_L is a lift coefficient which defines that component acting normal to the wind and in the plane containing the angle B. The coefficients apply to the exposed area of the guys, Ld, L being their chord length and d their diameter. The coefficients shall be used in conjunction with the effective velocity pressures of Table 8-1.

8.8.6 PATTERNS IN WIND LOADS: For guyed towers, a reduction of 25% of the design pressure in guy span between guys, shall be made for the determination of maximum and minimum moments and shears. The cantilever portion shall be designed for 125% of the design pressure.

TABLE 8-14

Net Pressure Coefficients for Square - and Triangular - Section Towers, C_f

ϕ	Square Towers	Triangular Towers
Less than 0.025	4.0	3.6
0.025 to 0.45	$4.13 - 5.18\ \phi$	$3.71 - 4.47\ \phi$
0.45 to 0.7	1.8	1.7
0.7 to 1.0	$1.33 + 0.67\ \phi$	$1.0 + \phi$

TABLE 8-15

Ratio of Drag on Towers with Rounded Members to Drag on Towers with Flat-Sided Members*

ϕ	Factor
Less than 0.3	2/3
0.3 to 0.8	$(0.66\ \phi + 0.47)$
0.8 to 1.0	1.0

* *For $d\sqrt{q} < 2.5$, where d = typical member diameter in feet and q = velocity pressure in psf*

TABLE 8-16

Wind-Loading Coefficients for Guys, C_D and C_L

β	10°	20°	30°	40°	50°	60°	70°	80°	90°
C_D	0.05	0.1	0.2	0.35	0.6	0.8	1.03	1.16	1.2
C_L	0.04	0.15	0.27	0.36	0.45	0.43	0.33	0.18	0

SECTION 8.9 OVERTURNING AND SLIDING:

8.9.1 OVERTURNING: The overturning moment due to the wind load shall not exceed 66-2/3% of the stabilizing moment of the building or other structure due to the dead load only, unless the building or other structure is anchored so as to resist the excess overturning moment without exceeding the allowable stresses for the materials used. The axis of rotation for computing the overturning moment and the moment of stability shall be taken as the intersection of the outside wall line on the leeward side and the plane representing the average elevation of the bottoms of the footings. The weight of the earth superimposed over footings may be used in computing the moment of stability due to dead load.

8.9.2 SLIDING: When the total resisting force due to friction is insufficient to prevent sliding, the building or other structure shall be anchored to withstand the excess sliding force without exceeding the allowable stresses for the materials used. Anchors provided to resist overturning moment may also be considered as providing resistance to sliding.

CHAPTER 9

FOUNDATIONS

SECTION 9.1 GENERAL: All buildings and structures constructed within Hurricane Hazard Zones A, B, C or D shall conform to these regulations (with special reference to Chapter 5) and the Building Code.

SECTION 9.2 SOIL INVESTIGATION:

9.2.1 GENERAL: The classification of the soil at each building site shall be determined when required by the Building Official. This determination is to be made by a Professional Engineer registered in the State of Texas.

9.2.2 INVESTIGATION: The soil investigation shall be carried out in accordance with the recommendations of the Soil Mechanics and Foundation Section of the American Society of Civil Engineers. As a minimum requirement for a single family residence, or similar structure, one test hole to a depth of at least 25 feet shall be drilled and penetration tests (or other approved tests) shall be performed to determine the density and bearing capacity of the foundation material. In a residential subdivision planned by a Professional Engineer, adequate tests may be performed to indicate the condition of the foundation material for all of the lots without requiring one test hole per lot, if approved by the Building Official.

9.2.3 REPORTS: The soil classification and design-bearing capacity shall be shown on the plans. The Building Official may require submission of a written report of the investigation which shall include, but need not be limited to, the following information: (1) plot showing the location of all test borings and low excavations; (2) description and classification of the materials encountered; (3) elevation of the water table encountered; (4) recommendations for foundation type and design criteria including bearing capacity, provisions to minimize the effects of expansive soils, and the effects of adjacent loads; and (5) expected total and differential settlement.

SECTION 9.3 DESIGN REQUIREMENTS:

9.3.1 GENERAL: All foundations shall be designed in accordance with the structural requirements of the Hazard Zone in which they are constructed.

9.3.2 HAZARD ZONE A: In Hazard Zone A the foundation of all buildings and structures will be designed to resist scour and soil movement, unless positive protection against scour and soil movement are provided. In addition, the foundation must be designed to safely transfer to the underlying soil all loads due to wind, water, dead load, live load, and all other loads (including uplift due to wind and water).

9.3.3 HAZARD ZONE B: Same as Hazard Zone A except no requirement for scour or soil movement.

9.3.4 HAZARD ZONE C: Same as Hazard Zone B except no battering forces.

9.3.5 HAZARD ZONE D: Same as Hazard Zone C except no flooding.

9.3.6 CONCRETE FOUNDATIONS:

9.3.6.1 PROTECTION OF REINFORCING STEEL: In Hazard Zones A, B, and C all concrete foundations shall be designed, detailed and constructed to provide a minimum of three inches (3") of concrete cover.

9.3.6.2 POSITIVE CONNECTIONS: All foundations shall be designed, detailed and constructed to provide positive connections between all members, pieces, and parts. These connections shall safely transmit all forces (compression, tension or shear) and moments required by the design. If reinforcing steel is to be welded, a test report must be submitted to prove that the steel is weldable.

SECTION 9.4 CONSTRUCTION REQUIREMENTS:

9.4.1 GENERAL: All foundations constructed in Hazard Zones A, B, C, and D shall be built in accordance with good Engineering practice. When required by the Building Official, a Professional Engineer registered in the State of Texas shall supervise the construction of the building or structure and shall submit periodic construction reports to the Building Official.

9.4.2 INFORMATION REQUIRED DURING CONSTRUCTION: The design engineer may be required to furnish to the Building Official any portion of the following information during construction: (1) a complete pile-driving log; (2) a report on the manufacture of all precast members including the stressing operation of prestressed members; (3) test reports from a certified laboratory on all concrete used, including precast members; and (4) mill certificates for structural and reinforcing metals used.

9.4.3 INFORMATION REQUIRED BEFORE FINAL ACCEPTANCE: When the structure is complete, and prior to final acceptance, the design engineer shall furnish the Building Official a complete set of As-Built drawings, together with his certification that the structure has been built in accord with the approved plans and specifications.

SUBJECT TO REVISION

CHAPTER 10

MASONRY WALLS

SECTION 10.1 GENERAL: All masonry walls of buildings and structures within Hazard Zones A, B, C, or D shall be designed, detailed, and constructed in accordance with the Building Code and these regulations.

SECTION 10.2 STRUCTURAL INTEGRITY:

10.2.1 GENERAL: All masonry walls shall be designed to resist all loads or combination of loads which are applicable in the Hazard Zone in which the structure is located. The walls shall safely transfer these loads to the supporting structure without disintegration or other structural failure.

10.2.2 TIE COLUMNS:

10.2.2.1 TIE COLUMN SPACING: Concrete tie columns shall be required in exterior walls of unit masonry. Concrete tie columns shall be required at all corners, at intervals not to exceed 20 feet center-to-center of columns, adjacent to any corner opening exceeding four feet in width, adjacent to any wall opening exceeding nine feet in width, and at the ends of free-standing walls exceeding two feet in length. Structurally designed columns may substitute for the tie columns herein required.

10.2.2.2 TIE COLUMN DIMENSIONS: Tie columns shall be not less than 12 inches in width. Tie columns having an unbraced height not exceeding 15 feet shall not be less in thickness than the wall nor less than a nominal eight inches, and, where exceeding 15 feet in unbraced length, shall be not less in thickness than 12 inches. The unbraced height shall be taken at the point of positive lateral support in the direction of consideration or the column may be designed to resist applicable lateral loads based on rational analysis.

10.2.2.3 TIE COLUMN REINFORCING: Tie columns shall be reinforced with not less than four #5 vertical bars for 8" x 12" columns nor less than four #6 vertical bars for 12" x 12" columns nor less reinforcing steel than 0.01 of the cross sectional area for columns of other dimensions nor less than may be required to resist axial loads or bending forces. Vertical reinforcing shall be doweled to the footing and splices shall be lapped 30 bar diameters. Columns shall be tied with #2 hoops spaced not more than 12 inches apart.

10.2.2.4 CASTING TIE COLUMNS: In load-bearing walls tie columns shall be cast only after masonry units are in place. Where masonry walls of skeleton frame construction are laid up after the frame has been erected, adequate anchorage designed by a Professional Engineer shall be provided. Where structural steel members are made fire-resistive with masonry units, the panel walls shall be bonded to the fire-resistive materials.

10.2.3 TIE BEAMS:

10.2.3.1 TIE BEAM LOCATION: A tie beam of reinforced concrete shall be placed in all walls of unit masonry, at each floor or roof level, and at such intermediate levels as may be required to limit the vertical heights of the masonry units to 16 feet.

10.2.3.2 TIE BEAM SIZE AND REINFORCEMENT: A tie beam shall be not less in dimension or reinforcing than required for the conditions of loading nor less than the following: A tie beam shall have a width of not less than a nominal eight inches, shall have a height of not less than 12 inches and shall be reinforced with not less than two #5 reinforcing bars in the top and two #5 reinforcing bars in the bottom of the beam.

10.2.3.3 CONTINUITY OF TIE BEAM: The tie beam shall be continuous. Continuity of the reinforcing in straight runs shall be provided by lapping splices not less than 18 inches or by adding two #5 bent bars which extend 18 inches each way from the corner. Continuity at columns shall be provided by continuing horizontal reinforcing in the columns or distance of 18 inches.

10.2.3.4 TIE BEAM AT GABLE END AND SHED END WALLS: A tie beam shall follow the rake of a gable or shed end.

10.2.3.5 TIE BEAM BOND: The concrete in tie beams shall be placed to bond to the masonry units immediately below and shall not be separated therefrom by wood, felt, or any other material which may prevent bond. Felt paper no wider than the width of the cells of the block may be used provided that it is depressed a minimum of 2 inches in one cell of each block.

10.2.3.6 PARAPET WALLS: Masonry parapet walls shall be not less than eight inches thick, shall be reinforced with minimum tie columns and shall be coped with a concrete beam not less than 64 square inches in cross section, reinforced with two #4 reinforcing bars. A parapet wall exceeding five feet in height above a tie beam or other point of lateral support shall be specifically designed to resist horizontal wind loads.

CHAPTER 11

STEEL & IRON

SECTION 11.1 GENERAL: Steel and iron members of buildings and structures constructed in a Hurricane Hazard Zone shall be designed, detailed, and constructed in accordance with the Building Code and these Regulations.

SECTION 11.2 COLUMNS: Tubular columns and other primary compression members, excluding secondary posts and struts not subject to bending and whose design load does not exceed 2,000 pounds, shall have a minimum least dimension of 2-1/2 inches and a minimum wall thickness of 3/16 of an inch.

SECTION 11.3 WELDING: Welding in the shop or field may be done only by persons who have been tested and certified by an approved testing laboratory for the welds to be performed, in accordance with the American Welding Society Standards.

SECTION 11.4 INSPECTION: A special inspector shall inspect the welding and high-strength bolting on buildings exceeding 10,000 sq. ft. in area or 3 stories in height or as required by the Building Official because of special conditions.

SECTION 11.5 OPEN-WEB STEEL JOISTS:

11.5.1 Where the net uplift force is equal to or greater than the load of construction, all web and bottom chord members shall have a minimum slenderness ratio of 200 and be proportioned to accommodate the maximum compression and tensile stresses.

11.5.2 The ends of every joist shall be bolted, welded or embedded at each bearing to provide not less resistance in any direction than 50 percent of the rated end reaction.

SECTION 11.6 COLD-FORMED STEEL CONSTRUCTION:

11.6.1 GENERAL: All structural members and connections shall be designed, detailed, and constructed to resist the loads applicable to the Hazard Zone in which it is constructed.

11.6.2 CONNECTIONS: All connections shall be by welding, riveting, bolting or other approved fastening devices or methods providing positive attachment and resistance to loosening. Metal screws shall not be used without positive provision for resistance to loosening. Fasteners shall be of compatible material, with consideration given to avoiding possible electrolysis.

11.6.3 STRUCTURAL SHEETS:

11.6.3.1 Decks and panels properly supported by and attached to the building frame, including but not limited to those having an approved fill material on their top surface, may be considered to act as diaphragms in resisting lateral forces where designed as such subject to the other limitations of the Building Code and these Regulations, except that metal without fill of less thickness than 22 gauge shall not be considered to have diaphragm value.

11.6.3.2 Poured fill on roof and floor decks shall not be assumed to have any structural value to support or resist vertical or lateral loads or to provide stability or diaphragm action unless so designed.

11.6.3.3 Positive attachment of sheets shall be provided to resist uplift and diaphragm forces. Attachment shall be as set forth in Paragraph 11.6.2 and not less frequently than the following maximum spacings or as required based on rational analysis and/or tests: (1) One fastener shall be placed near the corner of each sheet or at overlapping corners of the sheet; (2) Along each supporting member, the spacing of fasteners shall not exceed 8 inches on centers at ends of sheets nor 12 inches on centers at intermediate supports; (3) The spacing of edge fasteners between panels, and between panels and supporting members parallel to the direction of span, where continuous interlock is not otherwise provided, shall be not more than 12 inches on centers; and (4) Poured lightweight concrete fill will be acceptable as continuous interlock.

11.6.3.4 Wall panels shall be attached as set forth in sub-paragraphs 11.6.3.3(1), (2), and (3) preceding.

11.6.4 NONSTRUCTURAL SHEETS: Steel sheet sections not suitable by rational analysis for self-supporting structural sheets shall be termed roofing and siding. Roofing and siding shall be used only over solid wood sheathing or equivalent backing. Attachment shall be as set forth in Paragraph 11.6.3.3 except that connections shall not be more than 12 inches on center each way, and except that attachment may be by 8d nails or by No. 6 wood screws, in accordance with the standards of the National Forest Products Association.

11.6.5 PROTECTION OF METAL: Steel sheets used in Hurricane Hazard Zones shall be protected by being galvanized in accordance with ASTM A525 and have a minimum of 1.25 oz. class coating or be of an approved alloy or be otherwise coated to provide equal durability and protection. Abrasions or damages to the protective coating shall be spot-treated with a material and in a manner compatible to the shop protective coating.

11.6.6 WELDING: The fusion welding of structural members and structural sheets less than 22 gauge in thickness shall be through weld washers not less than 14 gauge in thickness and one inch in diameter, contoured if necessary to provide continuous contact, or through an equivalent device.

CHAPTER 12

WOOD

SECTION 12.1 GENERAL: Wood members and their fastenings shall be designed by methods admitting of rational analysis according to established principles of mechanics. All members shall be framed, anchored, tied and braced to develop the strength and rigidity necessary for the purposes for which they are used and to resist the loads imposed as set forth in the Building Code and these regulations.

SECTION 12.2 ALLOWABLE UNIT STRESSES:

12.2.1 Lumber used for joists, rafters, trusses, columns, beams, etc., shall be of a stress grade not less than 1000 psi nominal extreme fiber stress in bending.

12.2.2 Lumber used for studs in exterior walls and interior bearing walls shall be of a stress grade not less than 625 psi nominal extreme fiber stress in bending.

12.2.3 Lumber used for studs in interior non-bearing walls shall be of a stress grade not less than 225 psi nominal extreme fiber stress in bending.

SECTION 12.3 ANCHORAGE: Anchorage shall be continuous from the foundation to the roof and shall satisfy the uplift requirements of the design wind and/or flood.

12.3.1 Sills and base plates, where provided in contact with masonry, shall be of an approved durable species or be treated with an approved preservative and shall be attached to the masonry with 1/2 inch diameter bolts spaced not over 4 feet apart and embedded not less than 7 inches in the masonry.

12.3.2 Columns and posts shall be framed to true end bearing and shall be securely anchored against lateral and vertical forces. The bottoms of columns and posts shall be protected against deterioration.

12.3.3 Joists fire-cut into a masonry wall shall be anchored to the concrete beam on which they bear. Such anchors shall be spaced not more than four feet apart and shall be placed at opposite ends across the building on the same run of joists.

12.3.4 Joists shall be nailed to bearing plates, where such plates occur, to each other where contiguous at a lap, and to the studs where such studs are contiguous; and ceiling joists shall be nailed to roof rafters where contiguous.

12.3.5 Every roof rafter and/or roof joist shall be anchored to the beam or studs on which they bear, and roof rafters opposing at a ridge shall be anchored across the ridge as set forth in subsection 12.3.7.

12.3.6 Anchors securing wood to concrete shall be not less than 1" x 1/8" steel strap embedded in the concrete and nailed with three 16d nails to wood members. In lieu of such straps, anchorage may be as approved by the Building Official when designed by a Professional Engineer.

12.3.7 Anchors securing wood to wood shall be of 1" x 1/8" steel strap, nailed to each member with three 16d nails, or shall be a commercial anchor approved by the Building Official anchoring each member. All anchors and relative nails exposed to the weather shall be galvanized.

SECTION 12.4 STORM SHEATHING: Exterior stud walls shall be sheathed to resist the racking load of wind. Tightly fitted, diagonally placed, boards not less than 5/8 inch thickness, shall be nailed by three 8d common nails to each support for 1" x 6" boards and four 8d common nails for 1" x 8" boards. Plywood wall sheathing, 1/2 inch thickness, may be used in lieu of boards.

SECTION 12.5 CANTILEVER ROOF JOISTS: Roof joists may cantilever over exterior walls as limited by the allowable stress, but the length of such cantilever shall not exceed the length of the portion of the joist inside the building, and where the cantilever of tail joists exceeds three feet, the roof joist acting as a header shall be doubled.

CHAPTER 13

CONCRETE

SECTION 13.1 GENERAL: All concrete members of buildings and structures constructed within Hazard Zones A, B, C, or D shall be designed, detailed, and constructed in accordance with the Building Code and these Regulations.

SECTION 13.2 CONCRETE PROTECTION FOR REINFORCEMENT:

13.2.1 MEMBERS IN CONTACT WITH GROUND AND BELOW RFD: Concrete members which are constructed against the ground and members which are at or below the RFD shall have not less than three inches of concrete between the steel reinforcment and the concrete outer surface.

13.2.2 PRECAST UNITS: Concrete coverage of reinforcement in precast units shall be as set forth in the appropriate standard except that precast cement mortar units may have less cover than otherwise set forth, but not less than 1/8 inch providing: (1) The units are manufactured under the control, certification, and supervision of a Professional Engineer. (2) Reinforcing shall be galvanized, stainless steel or approved equal. (3) To insure exact final location of the steel, positive and rigid devices for that purpose are employed in the manufacturing process. (4) Cement mortar density shall be not less than 155 pounds per cubic foot, including reinforcing, and the minimum strength shall not be less than 5000 psi in 28 days. (5) Cement mortar shall not contain less than 1 part cement, by volume, for each two parts of fine aggregate. (6) Fine aggregate shall have a maximum size of 4.76 mm. (7) No coarse aggregate shall be used. (8) Units shall be cast on vibrating forms. (9) Members shall not be in contact with the ground or standing water. (10) Where required, fire-resistivity concrete cover requirement will control.

SECTION 13.3 PRECAST UNITS:

13.3.1 All precast structural items shall be designed by a Registered Professional Engineer.

13.3.2 Only the materials cast monolithically with the units at the time of manufacture shall be used in computing stresses unless adequate and approved shear transfer is provided.

13.3.3 The Building Official may promulgate and set forth in writing such reasonable rules for requiring tests to be made by an approved laboratory as he may consider necessary to insure compliance with this Regulation and the Building Code.

13.3.4 The Building Official or his representative shall have free access to the plant of any producer at all hours of normal operation, and failure to permit such access shall be cause for revocation of approval.

13.3.5 All connections shall be designed, detailed and constructed to safely transfer all wind, live and dead loads to the supporting structure without disintegration or structural failure.

CHAPTER 14

CLADDING AND GLAZING

SECTION 14.1 GENERAL: All cladding and glazing of buildings and structures constructed within Hazard Zones A, B, C, and D shall be designed, detailed and constructed in accordance with the Building Code and these Regulations. All exterior cladding, wall covering, windows, doors, glass and glazing shall be designed to resist loads (including suction) due to the applicable wind speeds and to meet requirements of flooding if located below the RFD. Connections for these elements must be designed to safely transfer the design loads to the supporting structure without disintegration or structural failure.

SECTION 14.2 LIMITS OF SIZE OF GLASS: Regular plate and sheet glass used in exterior walls shall not exceed the areas set forth in Table 14-1. The table applies for width-to-length ratios from 2:10 to 10:10. The allowable area of glass other than regular plate and sheet used in exterior walls shall not exceed the areas obtained by multiplying the areas in Table 14-1 by the following factors:

Tempered Safety Glass	4.0
Insulating (double glazed)	1.5
Rough Rolled Plate	1.0
Laminated	0.6
Wire Glass	0.5
Sandblasted or Etched	0.4

SECTION 14.3 DOORS AND OPERATIVE WINDOWS IN EXTERIOR WALLS: The design and approval of operative windows, sliding doors and swinging doors, including their support members in exterior walls shall be based on the proposed-use height above grade in accordance with Chapter 8 of these Regulations. Maximum glass sizes shall comply with Table 14-1.

TABLE 14.1

MAXIMUM AREA OF GLASS IN SQUARE FEET Wind Velocity Taken as 140 MPH at 30 Feet Above Grade										
	Glass Thickness (Inches)									
Height Above Grade	S.S.	1/8 & D.S.	3/16 & 13/64	7/32	1/4	5/16	3/8	1/2	5/8	3/4
0'-5'	7.3	11.4	22.0	27.2	33.8	47.0	60.1	88.2	119.8	150.6
5'-15'	6.0	9.2	17.6	22.0	27.2	38.2	49.2	72.0	97.7	124.2
15'-25'	5.0	7.6	15.4	17.6	22.8	31.6	41.1	60.0	80.8	101.4
25'-35'	4.3	6.8	13.2	16.2	19.8	27.9	36.0	52.9	71.3	89.6
35'-55'	3.9	6.1	11.8	14.0	17.6	25.0	32.3	47.0	63.9	81.6
55'-75'	3.5	5.4	10.7	12.9	16.1	22.8	28.7	41.9	57.3	72.7
75'-100'	3.2	4.9	9.7	11.8	14.7	20.6	26.4	38.9	52.9	66.9
100'-150'	3.0	4.6	8.8	10.8	13.2	19.1	24.2	35.3	48.5	61.0
150'-250'	2.6	4.0	7.7	9.4	11.8	16.2	21.3	30.9	41.9	52.9
250'-350'	2.3	3.5	6.8	8.3	10.4	14.0	19.1	27.2	37.5	47.0
350'-550'	2.1	3.1	6.1	7.4	9.2	12.9	16.9	24.2	33.1	41.9
550'-750'	1.8	2.8	5.4	6.6	8.3	11.6	15.4	22.0	30.1	38.9
750'-1000'	1.7	2.6	5.0	6.1	7.6	10.7	14.0	19.8	27.2	34.5
over 1000'	1.6	2.5	4.8	5.9	7.3	10.3	13.2	19.1	26.5	33.8

CHAPTER 15

ROOF COVERING

SECTION 15.1 GENERAL: All roof covering of buildings located within Hazard Zones A, B, C and D shall be designed, detailed, and constructed in accordance with the Building Code and these Regulations. The roof coverings and the connections to the supporting sheathing, deck, or structural roof member will be such as to provide for safe transfer of all applicable loads to the supporting structure without disintegration or structural failure. In general, all roof coverings shall resist the uplift forces given in these standards with at least a safety factor of 2.

SECTION 15.2 PREPARED SHINGLE ROOF COVERINGS:

15.2.1 Wood roof decks to which prepared shingles are applied shall be solidly sheathed. Sheathing shall be well seasoned and dry. Sheathing boards shall be at least 1 inch nominal dimension boards not over 6 inches wide. Plywood sheathing shall be at least 5/8 of an inch thick.

15.2.2 Attic spaces shall be vented with vent openings so placed as to circulate air in all parts of the attic.

15.2.3 Nails shall be of sufficient length to extend through the roof deck (sheathing).

15.2.4 Thick-butt asphalt shingles shall be nailed in the thick portion of the shingle.

15.2.5 All butts or tabs of asphalt shingles shall be securely spotted or tabbed with a plastic, fibrous, asphaltic cement or anchored by clips or locks, and all edges at eaves and gables shall be set in such cement 3 inches back from the edge.

15.2.6 Metal drip edges shall be nailed to the roof deck with nails not less than 10 inches on centers.

SECTION 15.3 BUILT-UP ROOF COVERINGS:

15.3.1 For built-up roof coverings cant strips shall be provided at the angle of roof and vertical surfaces.

15.3.2 Built-up roof coverings shall be carried at least 6 inches above the cant strip to a reglet in the parapet and covered with flashing caulked into the reglet. The reglet may be omitted at parapet walls, provided two layers of felt or the equivalent are carried across the top of the parapet under coping and down the parapet to the lower edge of the cant strip. The said layers are to run vertically, being properly lapped and cemented to the parapet.

15.3.3 All resinous places in the wood roof deck shall be covered with sheathing paper or unsaturated felt.

15.3.4 The first layer or anchor sheet shall be not less than 30-pound felt nailed 6 inches on center along a 2-inch lap and nailed 12 inches on center both ways, in the area between laps with tin caps and 1-inch nails; or shall be not less than two layers of 15-pound felt lapped 18 inches and nailed through both sheets on 6-inch centers along the lap and on 12-inch centers in the area between laps with tin caps and 1-inch nails; or, where the underside of the roof sheathing is to be exposed and its appearance considered, the first layer shall be not less than a 30-pound felt or two layers of 15 pound felt nailed 6 inches on centers along the rafters with tin caps and 1-1/4-inch nails, and nailed 12 inches on centers, both ways, between rafters, with tin caps and 3/4 inch nails.

15.3.5 Each additional sheet above the anchor sheet shall be thoroughly mopped between layers with a bituminous compound so that no layer touches an unmopped layer. Bituminous compound for mopping plys together shall be air-refined asphalt or coal tar pitch but shall not be any type of emulsion, cold or cutback liquid cement, oil or grease.

15.3.6 Gravel stop and drip strips, and eave and gable drips shall be not less than No. 26 guage galvanized metal, 16 ounce copper or 0.024 inch aluminum, with not less than 3-inch flange on roof and nailed with not less than 3/4 inch nails spaced not more than 6 inches apart.

SECTION 15.4 ROLL ROOFING:

15.4.1 Roll roofing shall be applied only over a smooth surface. Roll roofing shall not be applied over shingle roofs.

15.4.2 Roll roofing applied in a single layer shall be spot mopped and applied by concealed nail method with a minimum 3-inch head lap and a minimum 6-inch end lap properly cemented. Nail spacing shall be not less than 4 inches on centers.

15.4.3 Nails that secure roll roofing to the roof deck shall be driven at least 3/4 of an inch from the edge of the sheet.

SECTION 15.5 TILE ROOFING:

15.5.1 Tile roofing shall be laid over not less than one layer of 30-pound asphalt felt securely fastened by nailing with tin caps.

15.5.2 All tile shall be thoroughly watered with a hose before application.

15.5.3 Every tile shall be laid full length in portland cement mortar and, in addition, the first three horizontal courses shall be nailed. Under certain conditions additional nailing may be required to prevent tile from slipping. Mortar shall be not less than one part cement and three parts sand and not more than twenty-five per cent lime by volume.

15.5.4 All nails for flashing and tiles shall be copper.

SECTION 15.6 CORRUGATED METAL ROOFING, PROTECTED METAL ROOFING, CORRUGATED AND FLAT ASBESTOS CEMENT ROOFING:

15.6.1 When roofings of the above types are applied to wood roof decks they shall be secured with drive screws of sufficient length to extend through the roof deck. When applied directly to purlins and other roof members, they shall be secured with bolted strap fasteners, bolts or stud fasteners. Properly designed clip fasteners that are approved may be used in accordance with the conditions of such approval. Drive screws at least 4 inches in length may be used to secure these roofings directly to wood purlins.

15.6.2 Aluminum roofing when fastened to steel roof structure shall be insulated against electrogalvanic action.

SECTION 15.7 INSULATED STEEL DECK ROOFING: Insulated steel deck shall be secured by spot welding of clips or spot welding the sheets to the steel purlins.

APPENDIX A

SELECTED REFERENCES - HAZARD ZONE DELINEATION

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APPENDIX B

SELECTED REFERENCES - MODEL MINIMUM BUILDING STANDARDS

ANSI A58.1 Building Code Requirements for Minimum Design Loads in Buildings and Other Structures (New York, N.Y.: American National Standards Institute) 1972.

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Southern Standard Building Code, Revised (Birmingham, Alabama: Southern Building Code Congress).

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APPENDIX C

The following Texas cities have adopted the Southern Standard Building Code (1) without modification:

Beaumont	League City
Bridge City	Orange
Brownsville	Nederland
Clear Lake Shores	Port Aransas
Friendswood	Port Arthur
Groves	Port Lavaca
Hitchcock	Port Neches
Kemah	Pear Ridge
Lakeview	Texas City
La Marque	Webster

The City of Galveston has adopted the Southern Standard Building Code with increased wind pressures as follows:

Height	Wind Pressure
Less than 30'	30 psf
31' - 50'	42 psf
51' - 99'	54 psf
100' - 199'	60 psf
All elevations south of seawall	75 psf

The City of Corpus Christi has adopted the Southern Standard Building Code with the following modifications:

1. Added paragraphs concerning "Hurricane Precautions" and "Special Hurricane Inspection."

2. Increased wind loads:

Height	Wind Pressure
Less than 30'	30 psf
31' - 50'	40 psf

3. Established minimum lumber grade (1200 psi).

4. Added requirement for continuous anchorage in timber construction.

5. Established requirements for mobile homes.

6. Established more restrictive requirement for roof coverings.

The town of South Padre Island has a "Building Requirement" which apparently requires:

1. A wind load of 45 pounds per square foot at 30 feet above existing grade.

2. 35-foot piles on the Gulf side, 25 foot piles on the Bay side, and pile penetration of 5' below mean high tide under concrete slabs (no required penetration otherwise).

3. Anchorage continuous from foundation to roof.

Galveston County, in accordance with legislation concerning National Flood Insurance, has adopted the Southern Standard Building Code as a part of its building regulations. This document defines flood hazard areas and requires the lowest floor level of all new construction to be above the 100 year flood or 18 inches above natural ground, whichever is higher. Part V of the regulation includes some requirements for structural design and material use.

The City of Baytown requires compliance with the Southern Standard Building Code for commercial construction and FHA 300 Code (2) for residential construction.

Rockport requires compliance only with electrial and plumbing codes.

The above information is taken from a survey made by Dr. Charles Hix. This information is included only as a general reference, as in only one instance was the response to the survey provided by a person familiar with building codes and construction practices. Only four of the respondents to the survey furnished copies of ordinances adopting the standard code. In one instance the written response indicated that the standard code was in use without modification and a telephone call to a building official indicated that important modifications had been made to the standard code.